Indiana Lake Classification System And Management Plan

Indiana Department of Environmental Management

1986

FORWARD

Beginning in 1970 the State of Indiana recognized the need to generate physical, chemical and biological data from all of its public lakes and reservoirs. It was further recognized that these data should be organized into a system that would permit the comparison of one lake to the next and the prioritization of lakes and reservoirs according to their need for protection and/or renovation.

In 1971 the Indiana Lakes Studies Program gained momentum and become more organized in that study methods were standardized. However, the classification system was still in an evolutionary state and was not developed to its present form until 1972.

By 1975 essentially every public lake and reservoir in the State had been classified according to its trophic nature using the BonHomme Trophic Index. Several ranking tables were prepared using these data so that logical comparisons could be made. It was readily apparent that the data generated was quite voluminous and in a form generally suited for administrative use only. It was also apparent that there was a need to have an independent group of experts evaluate our classification system to determine if it was satisfactory for its intended use and to compare the BonHomme Trophic Index to other classification systems that were being used by other States. Finally, there was a need to organize these data in such a way as to provide the State with a workable Lake Management Plan.

Subsequently, a contract was entered into with Ball State University to accomplish these tasks. The following report represents the findings and recommendations of the study conducted by Drs. Torke and Senft of Ball State University. However, this report was updated in 1986 to include new data from 14 lakes as well as older data which was omitted from the original edition. This report was also expanded to include a more detailed description of the BonHomme Index and how it defines four broad lake eutrophication classes. Finally, the table of lakes and their characteristics (Appendix II) has been revised to include the appropriate management group for each lake.

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INTRODUCTION

Preservation and management of Indiana's lakes for enjoyment and use by present and future generations is a goal worthy of striving for, and one which has been adopted in principle by state and federal agencies. In order to deal with the multitude of lakes found in an area the size of the State of Indiana, a substantial body of information is needed on the types of lakes and types of lake problems which must be considered. Adequate information is a prerequisite for decision-making in all fields of human endeavor. When the amount of information is so large as to not be readily comprehensible, a classification system, to organize and facilitate analysis of the data, is necessary. Classification, then, is a defense mechanism on the part of the investigators who have accumulated too much information of be dealt with directly. However, classification is not a substitute for knowledge, nor does merely naming something imply that we know very much about it.

Classifications have been proposed in nearly every facet of man's total knowledge, but the type of classification used in a particular instance depends largely on who proposed it and why. Various criteria have been used for the classification of lakes. In this report, criteria which relate to lake trophic state are given greatest consideration. This is because the report focuses on nutrient inputs and other influences of human activity which tend to shift conditions in the lake toward the eutrophic end of the trophic spectrum. But it is recognized that for other purposes different criteria might be used, e.g., recreational use, water supply value, fish communities, and many others, although all such classifications will be affected in some way by the lake trophic state.

The process of classification, as it might be applied to lakes, has been reviewed by Sheldon (1972). He presents a classical approach to classification in defining the essential steps as description, comparison, and synthesis.

Description involves the gathering of data, either on the lake itself (aerial photography, depth soundings, water chemistry, and water transparency measurements, to name a few) or on man's interaction with the lake (histories of land and water use, residential problems surveys, economic studies, etc.). Lakes are all individuals, each with its own set of peculiar characteristics, both natural and man-made, not one being exactly like another. They can and should, nevertheless, be classified so that we can begin to identify and deal with the prevalent problems which impair their use and in some cases threaten their very life. Two considerations should be kept in mind when acquiring a data set. First, the data must be appropriate for the objectives of the classification, and second, the resulting classification can only be as good as the data which forms it. Both precision and accuracy in measurement as well as the amount, representativeness, and variability of the data will affect the usefulness and predictive value of the classification.

In classifications which are based on input for several different data sets, one must use various types of data transformations in order to make the data sets compatible, or to compare apples and oranges, so to speak. Logarithmic and other data transformations which alter the variance must be used with care, and their use should at least be supported with sound theoretical considerations. Although certain characteristics of lakes, which might be used in classification, are perhaps best measured with the use of an interval scale, data is most meaningfully measured when each data item is given in precise value. Data acquisition should be, and most often is, done on the basis of ordinal scales which allow for calculation of the variance of the data.

Secondly, the process of classification involves comparison, that is, measures of similarities and differences. With large data sets, the most widely used statistical measure is Euclidean distance, which is simply an extension of Pythagorean theorem to points in a multi-dimensional space. Various clustering and ordination techniques are based on this principle and have been applied to multiple data sets to produce various classifications. In recent years, workers have applied these methods to the classification of lakes (Beeton and Crumrine 1975, University of Michigan Biological Station 1974, Sheldon 1972). It is interesting to note that when classification of the same group of lakes is performed at different times of the year by these methods, somewhat different classifications result. The University of Michigan Biological Station (1974) measured 13 parameters in 37 lakes on a trimonthly schedule corresponding to the four seasons. Although, in the dendrograms produced by the cluster analysis technique, most of the lakes occurred in the same higher cluster for each sampling date, there were considerable differences between clusters at the lower levels, and a number of lakes occurred in more than one major cluster during the sampling period. It appears that such seasonal variations would limit the usefulness of the classification. Any classification for lakes based on discrete data sets, often widely separated in time, must by its very description contain imperfections. However, such a classification, despite its imperfections and biases, does produce an overall picture of the diversity and condition of the lakes which comprise it and, therefore, constitutes a knowledge base upon which some decisions can be made. It must be remembered, however, that the classification is only accurate within broad boundaries and that usually specific decisions for specific lakes must be based upon further study and data collection.

The third aspect in the process of classification is synthesis. The comparison of similarities and differences which are present in the data set leads to the placement of lakes into a series of categories which are all more or less related to each other. The problem of synthesis is the selection of boundaries for the categories. This process is often prone to be arbitrary. Careful screening of the data and intuitive judgment must precede this stage of classification. Rigorous adherence to systems of categories will create problems in decision-making and management. Thus, classification must be viewed as a tool which is only as useful as the knowledge base which supports it.

Classification systems must not be static but must evolve through the continual input of new information. We must bear in mind not only their usefulness but their limitations and the constant need for additional information as we approach specific problems.

Part I. A Review of Lake Classifications and Their Application to Indiana Lakes

A. Classification based on lake origin

In the vast array of scientific literature, several types of classification systems for lakes have been proposed. Some of these have received more recognition than others, and it is my purpose here to discuss and evaluate these systems in terms of applicability to classification and management of lakes in Indiana.

Hutchinson (1975) in his first volume of A Treatise of Limnology classified lakes on the basis of the constructive, destructive, and obstructive agencies producing their basins. This classification is really an expansion of the concepts set down by W. D. Davis (1882, 1887). Hutchinson recognized 76 types of lakes which originated as tectonic basins, lakes associated with volcanic activity, lakes formed by landslides, lakes formed by glacial activity, solution lakes, lakes due to fluviatile action, lake basins formed by wind, lake basins formed in association with shorelines, lakes formed by organic accumulation, lakes produced by the complex behavior of higher organisms, and lakes produced by meteorite impact. Hutchinson's system has since been followed by most general textbooks on limnology (Wetzel 1975, Cole 1975, Reid and Wood 1976, and brief mention in Ruttner 1963). In Indiana only, some of Hutchinson's types are represented and only a few are of major importance.

1. Lakes Formed by Glacial Activity

Although most of Indiana was subjected to four successive continental glaciations during Pleistocene times, only the last of these, the Wisconsin stage, created lakes which are in existence today. Glacial lakes of various types exist within the state. These include lakes in basins between terminal and lateral moraines, lakes in irregularities in ground moraine, lakes in kettles (depressions left by the melting of large buried ice blocks) in outwash, drift-filled valleys or pitted outwash plains, and lakes arising from morainal damming of valleys. Natural lakes in Indiana are largely of glacial origin and confined to two regions of glacial moraines in the northern part of the state, the Valparaiso Morainal Area to the west and the Steuben Morainal Area to the east. Approximately 500 lakes greater than ten acres in area are located in the northernmost tiers of counties (Frey 1966). Most of these are small, with an average area of 85 acres and an average maximum depth of 39 feet, although 13 of these are larger than 500 acres, and 19 have maximum depths exceeding 80 feet. Lake Wawasee is the largest (2,618 acres), and Tippecanoe Lake is the deepest (123 feet). Although most glacial lakes are concentrated in the northern counties, a few relicts are to be found in the central part of the state. Perhaps the southernmost glacial lake remnant is Lake

Galacia, a peat bog lake in Grant County (Leland Hardman pers. comm.). Many lakes and ponds formed by glacial processes have already accumulated enough sediments to become bogs or dry land. Some shallow basins have become dry within historic times due to changes in drainage patterns induced by forest clearing, agriculture, and other activities of man. Although Lake Michigan is beyond the scope of this report, mention should be made of this lake basin as an example of glacial scouring activity on an enormous scale.

2. Solution lakes

These are lakes occupying basins formed by the solution of limestone in karst regions. A considerable number of small ponds (sinkholes and swallowholes) are to be found in the karst region of the Mitchell plain in southern Indiana (Frey 1966). Many of these are either seasonal or intermittent over longer time periods, depending on the water regime of hypogean sources. Many of Indiana's caves contain subterranean "lakes," either expansions of underground streams, sinkholes to lower passages, or impoundments of subterranean streams such as occurs in Blue Springs Cave near Bedford, Lawrence County, where the dam on the East Fork of the White River at Williams has backed water up into the cave for some distance (Powell 1966). In general, solution lakes in the state are of interest from scenic and scientific standpoints but have little economic or recreational value. Presently, changes in drainage patterns and hydrological cycles and pollution from epigean sources threaten the aquatic biota of many Indiana caves (McReynolds 1976).

3. Lakes due to fluviatile action

These include lake basins formed either by dams due to sediment deposition of rivers or their tributaries, thus isolating a portion of the river channel (levee of lateral and delta lakes), or by the erosional action of rivers on mature flood plains cutting off and isolating loops of meanders (oxbow lakes). Examples of such basins are to be found associated with river systems throughout the state. An excellent series of oxbow cutoffs can be seen along the lower Wabash River valley. They are not, however, numerous enough to constitute an important major water resource of the state.

4. Lake associated with shorelines

These consist of basins isolated from larger lakes by sandbars or spits formed by the depositional activity of wind driven water currents. Little information is available on lakes of this type in the state. Presumably some small basins of this type are to be found in the Indiana Dunes shoreline of Lake Michigan. These are probably quite small and transitory in existence.

5. Lakes produced by the complex behavior of higher organisms

Aside from man, only the beaver has served as agent in the creation of lakes and ponds in Indiana. This, however, is a story of the already distant past. Beavers had been practically eliminated in Indiana by 1840. It is difficult to estimate from early writings the total effect of water conservation by this animal, but it must have been, to say the least, substantial. Beavers were reintroduced (Mumford 1966) in Indiana beginning in the 1930's. Though they are now found in nearly all sections of the state, they often do not build dams and lodges, but rather live in burrows dug in banks, as they often do in more populated regions of Europe and North America. However, there have been several cases in recent years of removal of beaver dams which had caused drainage and flooding problems (R. Hollingsworth pers. comm.). It is interesting to speculate about the possible dam-building activities of the giant bear-sized Pleistocene beaver, whose bones have been found in Indiana bogs.

Man has by far been the most powerful agent in both the creation and alteration of water bodies in the last century. Farm ponds and other artificial bodies of water on private lands have been constructed since early settlement times. Many of these originate as impoundments, but with the advent of heavy earth moving equipment it has become practical and even fashionable to excavate ponds with closed basins. Gravel pits, quarries, and strip mines are familiar examples of human excavation which may produce lakes on a larger scale. In the last two decades the excavation of borrow pits for the construction of ramps and overpasses along interstate highways has contributed a new aspect to the limnology of Indiana which is familiar to every motorist. However, by far the most important lakes produced by man are the large reservoirs which supply him with water, power, and public recreation.

Information on the origin or formation of particular lakes is of considerable value. Such information aids in the identification of groups of lakes with common characteristics and similar problems. Furthermore, information on lake origin gives insight into the geological, hydrological, and biological features of lakes, and this may be of special importance in identifying unique or unusual lakes which may deserve special attention and protection.

B. <u>Lake classifications based on morphometry and/or morphology</u>

A few authors have attempted to classify lakes on the basis of area and/or shape. Although many problems are associated with this typology, it would seem intrinsically sound to categorize lakes as being large or small or identify them by their shape. In general, the following statements may be made regarding the relationship of morphometry and other lake parameters.

1. Lake productivity is related to lake size in many situations, although numerous exceptions exist. Small lakes tend to be more productive than large lakes. Hayes (1957) found a direct relationship between surface area and mean depth for most lakes in his analysis of morphometric data from a series of 500 lakes. However, many exceptions to this rule exist. A comparison of the surface areas and volumes of Crooked Lake (surface acres = 802, mean depth = 44 feet, volume = 3.52×10^4 acre/foot) and Hamilton Lake (surface acres = 802, mean depth = 15 feet, volume = 1.20×10^4 acre/foot) in Steuben County

provides a dramatic example. Typically, lakes which have the euphotic zone in close proximity with the sediments are much more productive than lakes with large hypolimnetic volumes. Hayes, furthermore, found strong negative correlations between surface area and benthic faunal biomass and fish yield. Rawson (1955) found that morphometry was a dominant factor determining phytoplankton biomass for most of the large Canadian lakes he examined. He found that the average standing crop of net plankton varied from about 12-178 kg/ha in 20 lakes ranging from 0-250 meters in depth. Lakes with depths greater than 30 meters all showed phytoplankton crops of less than 35 kg/ha. Ryder (1961) proposed a "morphoedaphic index" (MEI) for lakes as a predicator of fish production. The ratio of total dissolved solids (TDS) to mean depth (Z) gives the MEI value. Oglesby (1977a, 1977b) examined the relationships of the MEI to phytoplankton standing crop and productivity and obtained relatively good relationships with the MEI on a log - log scale. That productivity should be related in a general way to lake depth is not surprising, and this relationship was noted since the early foundations of limnology in the beginning of this century.

2. Lake shapes often bear a relationship to the forces operating in their formation. Solution lakes are typically circular in shape. Oxbow lakes are crescent shaped. Coastal lakes formed by the development of a sand pit across the mouth of a stream valley are triangular. Impoundments or reservoirs created by natural or manmade dams are dendritic in form. Lakes of glacial origin show varieties of regular and irregular shapes.

Maximum length, maximum width, area and length of the shoreline are of primary importance for the lake morphometry. These can be measured directly from ground surveys or from appropriate aerial photographs. In addition, depth soundings to establish bottom contours should also be made. This allows for the calculation of volume and mean depth, the construction of hypsographic curves (Wetzel 1975), and is a requirement for the construction of hydrologic and nutrient budgets, to be discussed later in this paper. In Indiana, the U.S Geological Survey has, over the years, compiled morphometric information for most of the lakes.

Lake morphometry is a very important factor in lake management planning. Besides being an important factor in determining the overall trophic character of a lake, morphometry is an important factor for the selection of lake management techniques to be employed. Dredging, bottom sealing, and certain other restoration techniques are more practical for small lakes, whereas large lakes are perhaps best managed and protected by the use of nutrient input abatement techniques. The size and configuration of the lake, to a large extent, determines the choice and feasibility of particular lake management techniques.

C. Classifications based on hydrological features

Indiana is situated in an endorheic region, that is, an area where rivers originate and flow to the sea. Early records from pre-settlement times indicate that more of the land surface was previously under water than today.

It has been estimated that, by injudicious farming and deforestation, the water table has been lowered in the eastern United States by from 10 to 40 feet. At least three-fourths of the shallow wells and springs of this region failed shortly after deforestation. The original prevalence of wet terrain was often noted in the records of early settlement times (Lindsey 1966). Much of the area of the northern third of Indiana, and especially the northwestern part, was covered by extensive wetlands. Northeast of the present village of English Lake in Starke County was a 12-mile long lake of the same name, which was a wide permanent spread of the Kankakee River. The lake and its extensive marshes were drained in 1884. In northern Newton County, the Town of Lake Village is situated on the old shore of Beaver Lake, which in 1834 occupied a shallow basin of 28,500 acres. By 1917, drainage had reduced it to 10,000 acres and today it has completely disappeared. Settlement induced changes affecting water balance in Indiana include the clearing of forest lands for agriculture, the construction of canals and drainage ditches, channelization of streams, and the elimination of the once numerous beaver population.

Water can enter lakes from any of several sources (Hutchinson 1957). The importance of various sources varies with the size of the lake, the size of the drainage basin, geographic location, and local climate and topography.

1. Precipitation (rainfall directly on the surface of the lake is of more importance in larger basins).

2. Surface runoff (modified by topography and vegetation).

3. Ground water seepage (especially important for lakes with basins in glacial till or with rock basins and for solution lakes in karst regions).

4. Ground water entering as discreet springs (discreet springs are probably less frequently encountered in lakes than is popularly supposed).

5. Inlet streams (these are often the major source of water input in many Indiana lakes and all reservoirs).

Birge and Juday (1934) recognized two lake types on the basis of water loss. In drainage lakes, loss of water occurs by flow from an outlet. In seepage lakes, loss of water is by seepage into the groundwater from the basin walls. Some controversy exists (Hutchinson 1957) concerning the true nature of water income and loss in seepage lakes. In many such lakes it may be that seepage sources and losses really involve only very superficial ground water from above the clay seal in the lake basin which was formed during the early stages of the lake's development.

The Wisconsin Department of Natural Resources (Surface Water Resources of Wisconsin Counties, 1959-present) has classified Wisconsin's lakes into seven categories according to hydrologic properties and related features of water chemistry. This classification follows that of Prescott (1951) for the first four types of Wisconsin lakes, whereas three more types were added because they show easily recognized, definitive characteristics.

1. Hard water drainage lakes: Impoundments and lakes whose main water source is from stream drainage. Methyl purple (ph 4.8-5.4) alkalinity (or M.P.A.) of 50 ppm or over, year around. Usually a pH of 7.0 and above.

2. Soft water drainage lakes. Impoundments and lakes whose main water source is from stream drainage. M.P.A. below 50 ppm at least during part of the year or year around; usually have a pH below 7.0.

3. Hard water seepage lakes: Landlocked, or nearly so. Water levels maintained by groundwater table and bottom seal. M.P.A. of 50 ppm, or over; usually a pH of 7.0 and above.

4. Soft water seepage lakes: Landlocked, or nearly so. Water levels maintained by groundwater table and bottom seal. M.P.A. of less than 50 ppm; usually a pH below 7.0. Perhaps, the most common glacial lake type in Wisconsin.

5. Acid bog lakes: Small, usually brown water lakes of the kettle-hole type; usually landlocked or with only little outlet flow; only slight fluctuations of water levels; and encroaching marginal mats of vegetation of *Sphagnum*, leatherleaf, etc., from 50 percent of the shore. With pH below 7.0 and a low M.P.A.

6. Alkaline bog lakes: Small, brown water, kettle hole lakes with a stream meandering through them, with a pH above 7.0 and an M.P.A. medium to high.

7. Spring ponds (limnokrenes): Clear water, with groundwater flowing visibly out of the bottom of the basin and the overflow of which forms the beginning of a stream. Seldom freeze-over in winter. M.P.A. usually above 50 ppm with a pH neutral or above 7.0.

This type of classification is of value since it can easily be made using information obtained in cursory surveys, and the proposed categories convey meaning both to the limnologist and the general public. It is, however, most applicable to natural glacial lakes, and perhaps some additional categories should be added to include solution lakes and various man-made water-bodies.

Many lakes show seasonal fluctuations in water level, and some may also show water level fluctuations over long periods of time. Data on lake level variations are important because such variation may have direct consequences on the productivity of the body of water in question and its ability to metabolize organic materials coming into it. Also, fluctuations in lake level may involve the periodic flooding of low areas surrounding the basin proper, and these may be of importance in the spawning of fishes and growth and reproduction of fish food organisms.

Analytical techniques for the construction of water budgets or water balance models of lakes are complex and require a great deal of work and effort. Therefore, in the past, water budgets were constructed for only a few lakes. However, recent work in the U.S. and Canada has emphasized their potential importance. Water budgets are essential to the construction of nutrient budgets, discussed later in this paper, and therefore are likely to receive more attention in future studies. It is difficult to compare the nutrient dynamics of, for instance, seepage lakes with drainage lakes, unless one has some knowledge of the hydraulic retention time, since this will greatly influence actual nutrient concentrations within the lake.

A striking example of management of lake productivity by controlled hydrodynamics is seen in our large reservoirs. Studies on the hydrodynamics of TVA reservoirs have shown that water movements can become very complex in the presence of thermal stratification. Typically, reservoirs behave as large dimictic lakes exhibiting direct stratification in summer and indirect stratification in winter. This condition is somewhat modified by inflowing water from tributaries. Wunderlich (1971) distinguishes three basic types of inflow water movements which may result, depending on the type of stratification present in the receiving waters. Overflow involves inflowing water with a density less than the receiving reservoir water density. Hence, the inflowing water tends to spread out over the surface of the reservoir from the direction of the inlet. Underflow involves inflow water with density greater than the receiving reservoir water density. Thus, the inflowing water tends to flow along the bottom of the reservoir. Interflow involves inflow water with a density which is at first greater than, but eventually less than, the reservoir water density. In this case, the inflow water at first tends to flow along the bottom but upon reaching a depth where the density of the reservoir water exceeds that of the inflow water, flow then proceeds horizontally in that portion of the water column where density differences between inflow water and reservoir water are at a minimum.

A certain amount of mixing always accompanies the entrance of water into a reservoir, so that density differences between inflow and reservoir water are maximum at the upstream end of the reservoir and minimum or absent downstream. The type of flow patterns which occur have substantial influence on both oxygen and nutrient concentrations in the reservoir water. Reservoir outflows also will affect not only the temperature distribution but also the concentrations of dissolved substances in the reservoirs. Three types of outflows or intakes may be distinguished: high intake types which have the outlet near the water surface, intermediate intake type are at intermediate levels, and low intake types with outlets near the reservoir bottom. Various combinations of inflow and intake types produce a variety of flow patterns. If the inflow is of the overflow type and the intake is from the surface, flow is restricted to the surface water and deeper waters become stagnant and are isolated from the atmosphere. At the other extreme, if overflow is combined with bottom withdrawal, then the colder bottom waters are gradually replaced by warmer inflow waters. The temporary storage period of inflow water may vary from months to nearly all year around depending upon reservoir volume, inflow and outflow characteristics, reservoir operation, and other factors.

Hydraulic characteristics in reservoirs can be varied in order to maximize fish production and organic decomposition and minimize nutrient concentrations and algal bloom problems. It is necessary to monitor temperature distribution in the reservoir and its inflows and outflows on a seasonal basis in order to accomplish these goals. Much of the technology involved in reservoir management is presented by Hall (ed. 1971) in an extensive series of articles on reservoir fisheries and limnology.

D. <u>Classification based on the distribution of lake temperature</u>

The first attempt to classify lakes on the basis of temperature stratification cycles was that of Forel (1892, 1895). He called any lake in which the water undergoes the temperature of maximum density (4°C) twice a year a temperate lake. For lakes with a single circulation period he distinguished between tropical lakes, which have the water never being cooled below 4°C and circulation occurring in winter, and polar lakes, in which the water never rises above 4°C and circulation occurs in summer. Unfortunately, Forel's classification is an over-simplification and numerous exceptions are to be found.

Whipple (1927) modified Forel's system to include the effects of mean depth on circulation for each of Forel's lake types. It is as follows:

I. Polar lakes--Surface temperatures never above 4°C.

Order 1. Bottom water at 4°C throughout year; one circulation period possible in summer, usually none.
Order 2. Temperature of bottom water varies but not far from 4°C; one circulation period in summer.
Order 3. Temperature of bottom water very similar to that of surface water; circulation more or less continuous except when frozen.

II. Temperate lakes--Surface temperatures vary above and below 4°C.

Order 1. Temperature of bottom water at 4°C throughout year; two circulation periods possible (one in spring and one in autumn), often none.
Order 2. Temperature of bottom water varies but not far from 4°C; two circulation periods (one in spring and one in autumn).
Order 3. Temperature of bottom water very similar to that of surface water; circulation continuous except when frozen.

III. Tropical lakes--Surface temperatures always above 4°C.

Order 1. Temperature of bottom water near 4°C throughout year; one circulation period possible in winter.
Order 2. Temperature of bottom water varies but not far from 4°C; one circulation period in winter.
Order 3. Temperature of bottom water very similar to that of surface; circulation practically continuous throughout year.

Yoshimura (1936) further modified this classification and recognized five lake types, supposedly typical of the earth's climatic zones. An expansion of Whipple and Yoshimura's concepts was undertaken by Hutchinson and Loffler (1956) and is currently recognized as being the most useful classification with the least amount of ambiguity (see Fig. 1). The lake types emphasize circulation patterns rather than geographic location and refer to lakes that are of sufficient depth to form a hypolimnion.

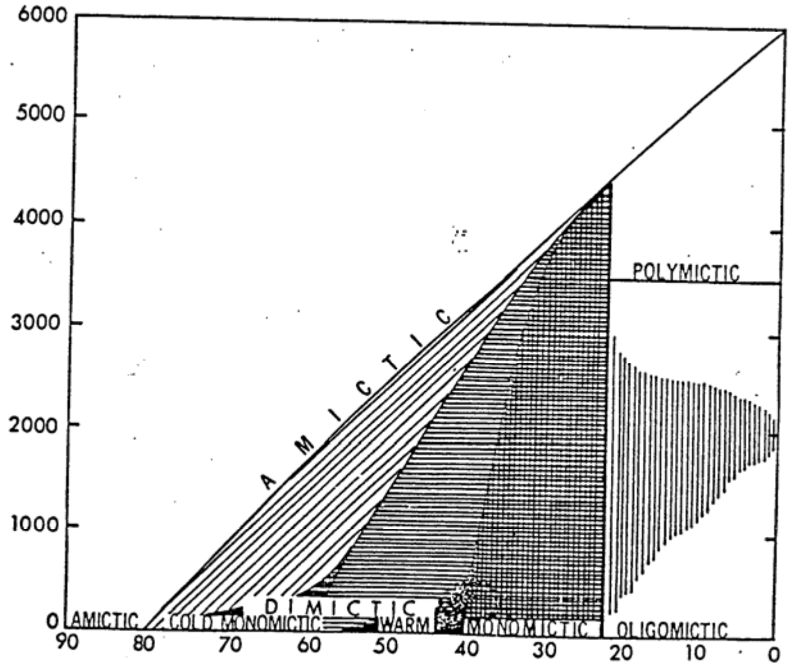
For lakes in Indiana, the following types can be recognized:

1. Dimictic Lakes: These are lakes which circulate freely each spring and again in the fall and they are directly stratified in summer and inversely stratified during winter. Most larger lakes in Indiana, including lakes of glacial origin and large reservoirs, belong to this group.

2. Polymictic Lakes: This type includes lakes with frequent or continuous circulation. Stratification is unstable and often of a temporary nature. Typically these are lakes of a relatively large area and shallow depth. Shallow ponds, lakes, and some reservoirs with a length sufficient to provide a strong enough wind fetch factor to allow for periodic overturn can be included in this group.

3. Meromictic Lakes: These lakes are characterized by a deep stratum of water that is perennially stagnant and separated from the upper water by a steep salinity gradient which is called a chemocline. Thermal stratification may form in the upper waters. The origin of such a lake may involve natural processes such as saline influx from salt deposits or springs, or from biochemically derived salinity as seems to be the case in Martin Lake, LaGrange County, Indiana, which has been shown to exhibit a temporary partial meromixis as the result of incomplete autumnal circulation occurring because of early ice cover (Wetzel 1973). Temporary biogenic meromixis is apparently not uncommon in lakes of our region and it is likely that it may occur in many Indiana lakes in certain years (Wetzel 1966). In addition, the introduction of salt used in road de-icing by surface runoff into lakes adjacent to roads and highways may create temporary or permanent meromixis of small lakes (Judd 1970). This may become a more severe problem as time goes on and salt accumulates in closed lake basins.

Figure 1. A thermal classification of lakes (modified from Hutchinson and Loeffler 1956) horizontal scale in degrees, vertical scale in meters. Dashed line indicates location of Indiana's lakes.



Lake mixing is of considerable consequence to nutrient availability and should be a factor of prime importance in the consideration of eutrophication abatement. The capacity of lake sediments to serve as a sink and source of nutrients varies according to the circulation patterns characteristic of the lake in question. Often polymictic lakes do not retain many nutrients in their sediments and, because of continual or periodic resuspension of these sediments, exhibit rapid and rather complete mineralization. In dimictic lakes, on the other hand, circulation periods are brief and the sediments are typically high in concentrations of both organic matter and nutrients.

Comparisons of lakes may be made on the basis of the capacity of the entire lake to absorb heat. Conceivably, a classification system could be constructed on a linear arrangement of heat budgets. Construction of heat budgets for lakes was first performed by Forel (1880), but his methods are unsatisfactory because he used maximum depth rather than mean depth or volume in his calculations. Birge (1915) refined the calculation of heat budgets, and his methods were later refined by Hutchinson (1957). Since annual heat budgets utilize both heat input and lake morphometry as factors in their calculation, it is probable that they bear a correlation with lake trophic conditions. Gorham (1964) found that annual heat budgets showed a strong semilogarithmic correlation with both mean depth and the square root of area for 71 lakes for which he had data. This supports the concept that lake morphometry is a primary factor in determining annual heat budgets, and the fact that morphometry is also a prime factor regulating lake trophy suggests that annual heat budgets may provide a baseline index for lake trophic state. Of course the relation between the two may be confounded by other factors, such as excessive allochthonous inputs.

E. Classifications based on biome association

It is tempting to borrow concepts and classifications proposed by terrestrial plant ecologists and apply these to lakes for several reasons. Lakes occur as islands within terrestrial biomes. The type of organic input, the nature of the lake's flora and fauna, and the visual appearance of a lake is determined to a greater or lesser extent by the terrestrial communities which surround it. Therefore, one might consider adopting a classification where lakes might be termed "boreal lakes," "eastern deciduous forest lakes," "cattail marsh lakes," etc. The use of dominant vegetational types plays an important part in the proposed "Classification of Wetlands and Deep-Water Habitats of the United States," currently under consideration by the U.S. Fish and Wildlife Service (Cowardin et al. 1977), but the authors do not strictly attempt to apply this concept to lake classification.

It would seem that such a classification for lakes would be either an oversimplification of the actual existing conditions or become bogged down with excessive details in attempting to define individual situations. However, information on the biome association of particular lakes may have merit in identifying lakes of exceptional value from scientific and aesthetic standpoints. Lakes with relatively undisturbed surroundings are a valuable resource for future generations to observe, study, and gain an appreciation of Indiana's past. The establishment of scientific areas and preserves has had a long history in the state (Lindsay, et al. 1969), but few of these areas have included lakes. More consideration should be devoted to the preservation of undisturbed natural lakes and other aquatic communities, before it is too late and the few remaining remnants are lost forever.

F. Classification based on trophic state

EARLY CONCEPTS

The fundamental concepts of lake classification on the basis of trophic state or productivity had their beginnings in the early part of this century. Weber (1907) in a study of the evolution of northern German peat bogs first introduced the terms "oligotrophic" and "eutrophic". He found that the deeper bog layers contained relatively large amounts of nutrients, which reflected a rich supply of nutrients in the lake which had preceeded the bog. The upper layers, formed during the terrestrial stage of the bog, were found to have relatively low concentrations of nutrients. A few years later, Einar Naumann studied phytoplankton and recent sediments of various Swedish lakes. In his first paper (1917), he postulated a direct relationship between nutrient availability (phosphorus and nitrogen) and phytoplankton composition and biomass. This conclusion was not based on analytical data, but rather on intuitive observation. In this paper, he applied some of Weber's ideas on peat bogs to recent lake deposits. In a second paper (1919), he used the terms "oligotrophic" and "eutrophic" to characterize different associations of phytoplankton. He also included a "heterotrophic" category for polluted waters. This was done in an attempt to coordinate his system with the saprobic system of Kolkwitz and Marsson (1902) which provided a zonation series for sections of river downstream from a pollution source. About the same time, August Thienemann (1918) in Germany distinguished between Baltic (eutrophic) and sub-Alpine (oligotrophic) lakes on the basis of hypolimnetic oxygen regime and chironomid midge larvae associations. Later (1921), he adopted Naumann's terminology and added a third category, dystrophic lakes for those lakes with humic waters. Thus, Naumann and Thienemann established the fundamentals of lake trophic typology or classification. Their ideas have had a great impact on limnological thought into the present time. However, some problems with this classification were already apparent in their time. Many lakes, either for morphometric, climatic, or other reasons did not fit the proposed scheme.

THE EFFECTS OF MORPHOMETRY AND OTHER PARAMETERS

Morphometric parameters can affect lake productivity in several ways. Epilimnetic waters with substantial concentrations of nutrients, if situated in large basins with large hypolimnetic volumes, will not produce enough organic matter over the growing season to cause complete oxygen depletion of the hypolimnion, whereas these same waters, if situated in a shallow basin, may quite rapidly create anaerobic conditions within the hypolimnion. Not only does the ratio of epilimnetic/hypolimnetic volumes affect productivity, but effects may be related to such parameters as shoreline development, which affects both external nutrient input, and absolute area. Area determines the strength of wind fetch and hence, in many lakes, is responsible for periodic introduction of nutrients by wind induced entrainment of hypolimnetic waters into the epilimon. Climatic effects are modified by both latitude and altitude, which affect the length of the growing season and the absolute amount of solar radiation. An arctic lake with a short growing season and long periods of ice cover cannot readily be compared to lakes in temperate and tropical regions, despite similarities in various physical and chemical parameters. In general, productivity tends to decrease with both latitude and altitude, but this effect may be modified within a given range for individual lakes. Productivity and trophic status are also affected by water income and export factors. The area and configuration of a lake's watershed will affect both the amount of water and nutrients entering the lake. The chemical composition of these incoming waters is affected by the underlying bedrock, soils, biota, and human activities within the watershed. The proportions of water entering the lake by streams, surface runoff, and direct precipitations will also affect the nutrient income and hence the productivity of the lake.

A multiplicity of terms has developed in an attempt to classify or pigeonhole lakes which deviate from the oligotrophic/mesotrophic/eutrophic spectrum for one or more reasons. Naumann (1932) introduced four new trophic types in addition to those he had previously proposed, and suggested no fewer than 24 individual and combined lake trophic types. Other authors have modified or expanded this system or merely added to it. Perhaps the most elaborate modification was proposed by Zafar (1959), whose system makes it possible to distinguish 2,016 lake types, on the basis of the ratio of Na and K to Ca and Mg, the concentrations of N and P, the quantity of humic materials, latitude, altitude, and the volume development index of Welch. Zafar further proposes that dominant plankton algal groups be recognized and included in his system of lake nomenclature so as to produce a name involving six individual symbols for each lake type. These elaborations have not survived the test of time, and none of them have received wide acceptance. Today the terms oligotrophic, mesotrophic, euthrophic, and dystrophic appear to be widely accepted, at least in limnological circles.

Birge and Juday (1927) made a significant contribution by distinguishing between autotrophic (produced internally within the lake) and allotrophic (external from within the watershed) sources of organic solutes. Today these terms are widely used to refer to sources and supplies of nutrients and other substances, as well as to the ultimate location of the production of organic material. Aberg and Rodhe (1942) defined the trophy of the lake as the intensity and kind of its supply of organic matter. The autotrophy of a lake indicates the intensity of its own total production or organic matter, whereas the allotrophy of a lake indicates the intensity of organic supply from its surrounding environment. According to Alberg and Rodhe, trophy should not be equated with nutrient levels as proposed by Findenegg (1955). However, as will be seen, the two are interdependent within a certain range.

Paleolimnology and Natural Eutrophication

A much clearer understanding of the process involved in eutrophication was gained by the advent of studies of lake development or evolution as evidenced by sediment cores. Early studies in Swedish lakes by Lundquist (1927) showed that lake sediments very often exhibit a stratigraphic sequence in which inorganic silt or clay is overlain by more organic sediments. Gams (1927) further showed that, in the Lunzer See in Austria, the older, less organic sediments contained fossils of chironomid midge larvae belonging to genera characteristic of oxygen-rich water, whereas the more recent organic sediments contained the fossilized remains of chironomid genera tolerating water containing very little oxygen.

Paleolimnological studies on glacial lakes in North America (Hutchinson and Wollock 1940, Deevey 1942) confirmed the results of these earlier studies in Europe. Typically, the newly formed lakes undergo an initial oligotrophic phase during which the nutrient concentrations and phytoplankton biomass increase slowly over time. This phase may in some cases occupy a time span of several thousand years. Several factors may be involved in the explanation of this phenomenon. Initially, low productivity may be accounted for by low postglacial temperatures and the erosion of glacial till, which would bury newly formed sediments and prevent the regeneration of nutrients until terrestrial vegetation and soils finally became well enough established to stop the erosion process. At this time terrestrial solids and vegetational succession in the watershed would exhibit low nutrient concentrations at first, but as time progressed, higher concentrations would predominate. Hutchinson and Wollock (1940) postulated that as small amounts of organic lake sediments were built up, these would reduce the pH, and therefore promote the solution of phosphorus and potassium. This in turn would promote greater algal production and hence more organic sediment production, which in turn would further promote the solution of nutrients. This whole process would continue slowly until an equilibrium was reached. This deceptively attractive hypothesis has been questioned by Livingston (1957) who argues that continued erosion of glacial till would bury newly formed sediments and thus prevent the regeneration of nutrients. He argues that the increase in nutrient input from terrestrial sources alone can account for the gradual increase in nutrients during the initial oligotrophic phase. The fact that most lakes of glacial origin have undergone an "initial oligotrophic phase" in the past was clearly shown in Deevey's studies (1942). One lake studied was exceptional in that, although it was only 11 meters deep at its formation, it nevertheless was initially oligotrophic, as shown in its sediment chemistry and chironomid midge fossils, even though, at the present time, any lake of that depth in that area would be eutrophic. It would seem, then, that oligotrophy really does precede eutrophy in the majority of basins of glacial origin, even though these may be quite shallow.

After some time, the input of nutrients from the watershed and recycling of nutrients from the sediments is balanced by the export of nutrients through the lake's outlet and/or by permanent loss to the sediments. This initiates a trophic equilibrium phase which is characterized by relatively stable and unchanging nutrient concentration and biological production. This phase may be of very long duration. In Linsley Pond in Connecticut, sediment cores show relatively unchanging conditions for a period of 7,000 years. The Lago di Monterosi in Italy was formed some 26,000 years ago as an explosion crater of a volcano. After a short oligotrophic stage, trophic equilibrium was established and continued for nearly 20,000 years, the lake becoming even more unproductive as nutrients were leached from the watershed. Pretty Lake in LaGrange County, Indiana was studied by Wetzel (1970), and this investigation dealt with looking at the distribution of sedimentary chlorophyll degradation products per gram of organic matter in sediment core samples which were aged by a C-14 technique. The lake was formed about 14,000 B.P., and after an initial oligotrophic phase, which lasted about 4,000 years, entered a trophic equilibrium phase, which has persisted up to the present with perhaps a slight overall decrease in the concentration of nutrients and production of phytoplankton.

Paleolimnology as a science (see reviews by Frey 1964, 1969, 1974) has relied on the examination of various parameters measured in sediment cores. Inorganic constituents frequently measured include silica, NaCl, Ca, K, P, N, Mn, and Fe. Sedimentary nutrients, phosphorus, and especially nitrogen, have been useful in elucidating trophic changes within the lake basins. Organic constituents, amino acids, carbohydrates, and others have not been very useful, except for pigments, because most are not stable and tend to be hydrolyzed enzymatically and chemically and then metabolized microbiologically. Photosynthetic pigments, however, have been a very useful measure of quantitative and qualitative changes. Furthermore, since pigments are characteristic of various algal types, much information on the changes in community structure can be obtained. Pollen from terrestrial vegetation has also been investigated in numerous studies and, although pollen does not originate within the lake ecosystem, pollen sequences may give some clues about nutrient inputs from the watershed. The appearance of ragweed (Ambrosia) pollen signals the settlement and clearing of the land by man and usually correlates very well with other parameters which indicate rapid cultural eutrophication. Algal remains, especially the silica frustules of diatoms, have value as indicator species of trophic conditions. The remains of animals in sediments are also important as indicators. Chironomid midge larvae and chydorid cladocera are usually the most abundant fossils and have been most frequently used to map patterns of lake development.

The tropic equilibrium phase comes to an end when sedimentation reduces the lake volume and mean depth beyond a certain point. After this point is achieved, the littoral plant community rapidly expands to the limnetic regions, and completely dominates the metabolism of the lake. The concept of lake evolution as proposed by Lindemann (1942) has often been presented in elementary college texts as the universal situation for all lakes. According to Lindemann's studies on Cedar Bog, Minnesota, a lake gradually becomes shallower with increasing sedimentation and then in a relatively short period of time becomes a bog. When sediments produced by bog vegetation exceed the water table a terrestrial plant community finally results. Although many lakes do progress through this sequence, it is far from the rule. According to Wetzel and Allen (1970), oligotrophic glacial lakes in temperate regions follow one of three routes toward extinction. If drainage inputs into the lakes are noncalcareous in nature, and there is a high allochthonous input of organic material, a bog lake will typically result. The bog will be characterized by the dominance of sphagnum moss forming a mat at first in the littoral regions, and gradually extending toward the center of the lake as the sphagnum continues to decrease the volume of the lake by the production of peat. Sphagnum species, even when dead, behave as cation exchangers and hence are responsible for the acidic conditions of most bogs. Although bog lakes have generally been considered to be unproductive, this conclusion is based on consideration of the phytoplankton production. Actually bogs are highly productive communities with most of the production carried on by sphagnum and other higher plants of the bog community. Bog lakes reach extinction when the deposition of peat exceeds the water tables. If, on the other hand, an oligotrophic lake receives high sustained calcareous inputs, this will result in the precipitation and deposition of calcium carbonate or marl. Paleolimnoligical studies have shown that many lakes of glacial origin were initially marl lakes. However, as calcium carbonate was depleted from the watershed and the input of dissolved organic material increased with the development of surrounding terrestrial vegetation, the ontogeny of these lakes proceeded in a different direction, either becoming a bog system or a eutrophic lake, eventually undergoing marsh succession. In some lakes, high inputs of carbonate have been maintained over long periods of time. In these situations marl deposition may proceed until the basin is filled. However, in most marl lakes a depletion of calcium carbonate leads to eutrophication. The apparent oligotrophy of marl lakes is maintained by decreased nutrient availability rather than a deficiency of nutrient input. Phosphorus and essential inorganic micronutrients, particularly iron and manganese, form highly insoluble compounds and are effectively lost in entirety from the trophogenic zone of marl lakes (Wetzel 1972). A third alternative occurs when a oligotrophic lake achieves a decrease in volume by sedimentation in the basin to the point where there is a substantial increase in inorganic nutrients both from loading from the watershed and regeneration from the sediments. This leads to a gradual eutrophication of the lake, increased sedimentation, and as the basin becomes shallow, an expansion of the littoral macrophyte community. A common successional pattern for shallow basins in our region involves the following communities: Macrophytes and associated microflora, reed swamps (Phagmites, Cyperus, Scirpus, Carex, and Typha), marsh (moderate size grasses and various tall dicots), and terrestrial vegetation. The point at which a lake enters the extinction phase is dependent upon the depth of the lake and the rate of nutrient input and, therefore, the rate of sedimentation within the lake basin. Many small ponds of glacial origin in Indiana have already become bogs or marshes, whereas deeper lakes are still a long way from entering the extinction phase. One of the primary concerns in consideration of the effects of cultural eutrophication is the very rapid increase in sedimentation rates which reduce the depth and volume of lakes in relatively short periods of time.

Nutrients and Eutrophication

It is quite apparent from numerous studies that nutrient inputs are the fundamental cause of the phenomena collectively known as cultural eutrophication. The importance of phosphorus and nitrogen has been the subject of major symposia and reviews. In lakes of the north temperate zone, there can be little doubt that phosphorus is the limiting nutrient, that is, the element in shortest supply necessary for algal growth. That phosphorus enters into the energy metabolism and the genetic material of plants, including algae, has been known for a long time. The most important form of phosphorus for algal nutrition is ionized PO_4 or dissolved inorganic phosphorus. Phosphorus in water can be detected in several forms. The most commonly measured forms are dissolved inorganic phorphorus (PO_4), dissolved organic phosphorus, and particulate phosphorus. Particulate phosphorus consists largely of phosphorus present in living bacterial and algal cells. Studies concerning the equilibria of the main phosphorus fractions in water have been conducted by Watt and Hayes (1963) and Rigler (1956-1964). A detailed study of the roles of bacteria and algae in the rapid recycling of phosphorus within the plankton community has been undertaken by Lean (1973). In lakes that are relatively unaffected by phosphorus inputs related to man's activities, it is apparent that phosphorus not only is a limiting nutrient at various times of the year, but also that the plankton community has evolved methods for the conservation and reuse of this dynamic element (Schindler 1977).

When one examines the results of studies on the phosphorus requirements of different algal species in laboratory culture, a pattern emerges which corresponds with the changes in algal species composition observed in lakes which have become eutrophic in recent times. Oligotrophic species such as *Fragilaria crotonensis*, *Asterionella formosa*, *Tabellaria fenestrata*, and *Dinobryon spp.* have low minimum phosphorus requirements, ranging from 0.2 g/mm^3 for *Asterionella* to 0.45-0.6 g/mm^3 cell volume for *Tabellaria*, whereas eutrophic species such as the green alga *Scenedesmus* and the blue green algae *Oscillatoria* and *Microcystis* have minimum phosphorus requirements in excess of 0.5 g/mm^3 cell volume. The progression from oligotrophic diatom communities with *Asterionella*, *Fragilaria*, and/or *Tabellaria* as dominants to eutrophic communities dominated by cyanophytes such as *Oscillataria* and *Microcystis* in lakes experiencing rapid cultural eutrophication is well documented by numerous examples in North America and Europe as well, although certain modifications of this typical progression have been noted in some lakes.

The relationship between nitrogen concentration and algal growth rates is somewhat less well known than that of phosphorus. The use of nitrogen in fertilizers for promoting the growth of terrestrial crop plants would indicate that the same effects might be expected for algae in lake water. Vollenweider (1971) has reviewed the literature on nitrogen and algal growth rates and has concluded that, where overall production is low, the limiting factor is usually phosphorus, although at this level of production the amount of nitrogen available is sufficient. However, where production is higher, the relationship may be reversed and nitrogen can act as a limiting factor. Therefore, providing that sufficient phosphorus is present, adding nitrogen can stimulate algal growth, especially in more eutrophic situations. Nitrogen is found in natural waters in various forms, as dissolved elemental nitrogen (N_2), ammonium (NH_3), nitrate (NO_3), nitrite (NO_2), and as dissolved organic nitrogen. Of these forms, organic nitrogen can be used as a nitrogen source for almost all bacteria, algae, and higher plants; ammonium by most bacteria, algae and higher plants; nitrate by algae and higher plants, for which it is usually the primary nitrogen source; and elemental nitrogen by some bacteria and some blue green algae which have the capacity of nitrogen fixation. Nitrite, which is toxic to humans at higher concentrations, is typically present in natural waters only at very low levels and is of little, if any, importance in aquatic plant nutrition. The ability of certain blue green algae to fix elemental nitrogen is of special interest since this ability may preclude nitrogen from becoming a limiting nutrient in the presence of excess phosphorus.

Consequences of Cultural Eutrophication

Cultural eutrophication is defined as the increase of productivity and sedimentation rates in lakes as a direct consequence of the activities of man. It is often difficult to make clear distinctions between the problems of eutrophication and other problems associated with man's activities, such as erosion caused by poor land use activities and certain pollutant sources producing toxic effects on aquatic organisms. Often these and other conditions occur along with, and are interrelated with, the effects of nutrient enrichment.

In defining the problems of eutrophication, one must separate the causes and effects. Usually the effects, in cases of advanced eutrophication, are obvious even to the casual observer, whereas the causes may or may not be easily identified and eliminated. Vollenweider (1971) distinguishes the following symptoms as being typical of incipient cultural eutrophication:

1. An increase in the quantity of the biomass of either the aquatic macrophytes and periphytic algae near the shore or of the algae of the open water regions or both. Usually such increases are accompanied by a decrease in the number of species that are typical of oligotrophic waters and, concurrently, by an increase in the number of characteristically eutrophic species.

2. Changes in both the number and types of animal species in the littoral, benthic, plankton, and fish communities. In the very beginning stages of culturally induced eutrophication, an initial increase in biomass of various segments of the animal community is often observed. At a more advanced state of eutrophication there is typically a shift of oligotrophic species to eutrophic and facultative species. In lakes of north-temperate regions, salmonid and coregonid fishes are typically replaced by centrarchid and cyprinid fish which are more tolerant of the existing conditions.

3. Physical and chemical changes include a decreasing water transparency and an accompanying change in water color. There is often a development of an oxygen maximum or minimum in the metalimnion, and in severe cases this condition may alternate on a diurnal basis. Because of an increased input of organic materials to the sediments, there is a gradual overall decline in the oxygen concentration of the hypolimnion during the period of summer thermal stratification. There is an increase of the average nutrient level, that is, concentrations of phosphorus and nitrogen, which can easily be detected by chemical methods.

As the process of eutrophication advances, all of these symptoms become more pronounced, finally leading to almost catastrophic changes. This advanced state is usually characterized by massive blooms of blue-green algae (*Oscillatoria*, *Anabaena*, *Aphanizomenon*, etc.); an enormous proliferation of aquatic macrophytes, periphyton, and floating algal mats along the lake shore; the total elimination of oxygen from the hypolimnion during the summer; the accumulation of considerable quantities of phosphorus and nitrogen; the appearance in the hypolimnion of hydrogen sulphide, ammonium ions, iron and manganese, non-mineralized organic substances and sometimes the formation of methane; the disappearance of benthic fauna in the deeper regions of the lake; and massive fish kills. Such changes present serious consequences for man's use of the lake. Besides the drastic losses incurred from an aesthetic standpoint, difficulties in terms of water use and human health result. Because of problems with filter clogging, precipitates of iron and manganese, pronounced corrosion, unpleasant taste and odor, etc., direct use of water for drinking and industrial purposes is severely impaired. From the recreational standpoint, advanced eutrophication is highly detrimental and gives rise to various unpleasant situations, such as various forms of skin irritation known as swimmer's itch, more frequent insect bites, tangling of motor boat propellers in weeds, and poor fishing. It is obvious that such changes do have serious repercussions on the economic value of lakes and their surroundings including local governments, industry, resorts and other recreation based business, fisheries, cottage owners, and local residents. Therefore, preventative and corrective measures to curb the effects of eutrophication are highly desirable to all concerned.

Trophic Parameters

The following discussion deals with various lake characteristics which are directly or indirectly influenced by the degree of lake trophy, and therefore closely interrelated. It is again emphasized that these parameters are largely correlated with the level of nutrient inputs to the lake basin.

A. Annual Oxygen Regime

In dimictic lakes of the temperate region, thermal stratification creates a distinct separation between the zones of autotrophic production (trophogenic zone) and decomposition (tropholytic zone). Because the hypolimnion is effectively isolated from the atmosphere, the quantity of oxygen present in the hypolimnion can only be affected by processes which decrease it. This suggests that the rate of hypolimnetic oxygen depletion is a useful measure of the organic production which has occurred in the lake. The use of oxygen deficits as an approximation of lake productivity was first proposed by Birge and Juday (1911) in Wisconsin and later used by Thienemann (1928) in Europe. Typically, in very oligotrophic lakes under thermal stratification, vertical oxygen profiles show very little changes in concentration with depth. Changes in oxygen concentration are determined largely by solubility at different temperatures rather than by biological processes. In very eutrophic lakes oxygen concentration in the epilimnion are comparable to or higher than those of oligotrophic lakes, but oxygen is reduced or absent in the hypolimnion. In this case, photosynthesis in the epilimnion maintains high concentrations of oxygen, whereas decomposition of the organic material produced in the epilimnion removes oxygen from the lower waters. These represent the extremes, and many lakes are intermediate. Some lakes exhibit oxygen maxima at the thermocline. A heterograde oxygen distribution of this type is due to high rates of photosynthetic activity in the metalimnion. Metalimnetic oxygen maxima in Indiana lakes have been studied by Eberly (1959, 1963, 1964). His studies indicate that metalimnetic oxygen maxima occur in lakes with surface areas small relative to the maximum depth. Such steep sloped lakes are also usually protected from wind action by surrounding topography and vegetation. Eberly found that the oxygen peak coincided with the zone of maximum photosynthesis by photoplankton and the depth of maximum growth of rooted aquatic plants in the littoral zone. The relative contributions of phytoplankton and macrophytes are dependent to a large degree on the size of the lake.

Several types of oxygen deficits have been proposed. The actual oxygen deficit refers to the difference between the observed oxygen concentration and the saturation value at the observed temperature of the water at the pressure of the lake surface. This measurement is not particularly useful since it assumes that the water at depth was saturated at the observed temperature during spring turnover. The absolute oxygen deficit is defined as the difference between the observed oxygen concentration and the saturation value at 4°C at the pressure of the lake surface. This measure also assumes complete oxygen saturation of the water column during spring circulation. The relative oxygen deficit (Strom 1931) is the difference between the observed oxygen content of the hypolimnion at some time during stratification and the observed oxygen concentration at the end of spring turnover. The relative aerial deficit is then defined as the mean deficit below 1 cm^2 of hypolimnetic surface of the individual deficits of a series of layers of decreasing volume with increasing depth. Although this measure would seem to be ideal for the approximation of total lake production, the method rests on several assumptions which may or may not be true. The hypolimnetic water must be relatively well isolated from the atmosphere and from oxygen exchange. Small lakes with steep sheltered basins and lakes under ice cover will adhere to this requisite most closely, but other lakes with larger relative surface areas may undergo some entrainment of hypolimnetic water into the hypolimnion at times of high wind stress, as might occur during severe storms, and, of course, very shallow lakes with large surface areas often exhibit no permanent thermal stratification and are subject to frequent turnover. Since oxygen deficits are an attempt to measure autochthonous production occurring within the lake, it is assumed that inputs of allochthonous organic water produced outside of the basin are relatively small and negligible. It is also assumed that most of the organic matter synthesized by phytoplankton in the trophogenic zone decomposes in the hypolimnion. This inevitably must lead to underestimates in most lakes since some decomposition usually does occur in the eplilimnion and metalimnion. Furthermore, it is assumed that decomposition in the hypolimnion is complete. This assumption is most certainly wrong. Partially decomposed organic matter will be incorporated permanently in the sediments, and the proportion lost in this way increases in lakes of higher productivity. Finally, oxygen deficit measurements can only be used to calculate oxygen matter production rates as long as the hypolimnion remains aerobic. When oxygen depletion is complete, no further measurements of oxygen decline can be made. Despite these difficulties, the use of oxygen deficits for relative comparison of lake trophic states has great value and is frequently done. The use of relative aerial oxygen deficits has a great advantage because the measurements are easily taken and do in most cases indicate gross trophic differences. Hutchinson (1938) evaluated oxygen depletion rates for data from several European and North American lakes, and arbitrarily delineated limits for lakes of different trophic categories. Mortimer (1941-1942) suggested rather different limits.

Lake Trophic Type	Hypolimnetic O_2 Depletion Rate	
	Hutchinson	Mortimer
Oligotrophic	0.017 mg cm^{-2} day^{-1}	0.025
Eutrophic	0.33	0.055

These limits are, as stated, somewhat arbitrary, but should be useful in defining ranges, especially when used in conjunction with other trophic parameters.

Often, data for the estimation of oxygen deficits is inadequate or lacking, and the available data only reveal the distribution of oxygen in the water column on a particular sampling date. Such information is, however, still useful in comparing different lakes if they were sampled at approximately the same time, and if something is known about their thermal stability.

B. Annual Distribution of Total Inorganic Carbon

In oligotrophic lakes there is little CO_2 accumulation in the hypolimnion. This reflects low phytoplankton productivity, and hence low deposition rates of organic matter to the sediments. As with oxygen concentration, the vertical distribution of the total CO_2 in oligotrophic lakes is influenced primarily by the effect of temperature on solubility. Eutrophic lakes exhibit a pronounced increase of total CO_2 during stratified periods, leading to very high concentrations in the hypolimnion before fall turnover. Typically, an inverse relationship is exhibited by pH. Changes in the concentration of the total CO_2 in the hypolimnion have been used to estimate indirectly the organic production of the trophogenic zone of the lake. Ruttner (1931) first suggested this, and later Einsele (1941) used this technique along with several other estimates of phytoplankton production and found them to be in close agreement. The most comprehensive evaluation of hypolimnion CO_2 accumulation as a measure of productivity was performed by Ole (1934, 1952, 1956). Unlike the oxygen deficit method, this method has the advantage of allowing for the measurement of change under both aerobic and anaerobic conditions. Furthermore, since carbon is a fundamental element in metabolic processes, the total CO_2 is, from this standpoint, one of the best parameters to measure. The assumptions underlying this method are the same as those discussed for oxygen deficits. In spite of the fact that this method is superior to the oxygen deficit method in several respects, it has not received much use in this country. Total CO_2 accumulation rates are easily calculated from pH and alkalinity measurements and should be given more attention as a comparative measure of lake trophic status than has been done in the past.

C. Nutrient Concentration

Although it is intuitively obvious that the trophic status of a lake is to a large extent controlled by the concentration of nutrients present in its waters, only recently have workers attempted to arrange lakes in a trophic series on the basis of the concentrations of nitrogen and phosphorus. Phosphorus, in particular, is generally charged to be the nutrient most frequently controlling eutrophication. That this is the general concensus of the scientific community has been pointed out in the National Academy of Science volume, Eutrophication: Causes, Consequences, Correctives (1969), and the proceedings of a special symposium of the American Society of Limnology and Oceanography, Nutrients and Eutrophication (1972). Furthermore, numerous experiments with algal cultures and whole lake experiments (Schindler, Armstrong, Holmgren, and Brunskill 1971) have clearly shown that enrichment with phosphorus, but not carbon or nitrogen alone, will bring about increased biomass of the phytoplankton. Another important consideration presented by Vollenweider (1978) is that the input of phosphorus will, for most lakes, be easier to control than that of nitrogen. Vollenweider argues that such phosphorus supplied to lakes is introduced via point sources (sewage, detergents, and industrial wastes), while nitrogen, although also supplied from point sources, is often introduced in large quantities from other sources (agricultural runoff, nitrogen fixation, precipitation) that are much more difficult to regulate. Therefore, from a standpoint of lake restoration, attention should be focused on the removal of phosphorus. However, for the purposes of lake trophic classification, nitrogen concentrations may be quite useful since they usually bear a close relationship to other trophic parameters. Numerous studies have confirmed the correlation between high levels of nitrate and ammonia and associated high levels of phosphorus. Leuchew, et al., (1970) found a very close relationship between both phosphorus and nitrogen concentrations and other trophic parameters for 12 Wisconsin lakes. Their data is based on annual means for monthly samples, and therefore probably reflects actual average conditions. The use of phosphorus concentrations for the trophic characterization of lakes must be exercised with care. The variability of phosphorus concentrations both seasonally and spatially within a lake is caused by several factors, including uptake and release of phosphorus by the sediments and the phytoplankton community and dispersal by currents. If only single measurements are available, these are best taken at the time of turnover. Measurements taken during periods of thermal stratification must be averaged for the entire water column. In some cases, considerable variation may be encountered with distance from the lake's inlet. Various forms of phosphorus are detectable in lake water by use of sample treatment procedures, such as filtration, acid hydrolysis, and digestion. The measurement of all of these "forms of phosphorus" is dependent on the reaction of phosphorus with molybdate. Perhaps the most commonly measured forms are orthophosphorus and total phosphorus. Orthophosphorus (PO_4) is a highly labile substance which is subject to very rapid exchange rates with other forms of phosphorus present in water (Lean 1973). Nevertheless, the concentration of orthophosphorus in lakes usually bears a close relationship to total phosphorus (Vollenweider 1968). Total phosphorus is the measurement of choice, since it includes phosphorus which is bound in living organisms and organic compounds as well as inorganic phosphate. Vollenweider (1968), using the data of Thomas (1953) on Swiss lakes, established the following relationships between nutrient concentrations and trophic status:

	Trophic Characteristics	Total P (mg/m^3)	Inorganic N (mg/m^3)
1.	Ultra-oligotrophic	5	200
2.	oligo-mesotrophic	5-10	200-400
3.	meso-eutrophic	10-30	300-650
4.	eu-polytrophic	30-100	500-1500
5.	polytrophic	100	1500

A similar classification was proposed by Sakamoto (1966) for Japanese lakes:

	Total P (mg/m^3)	Total Bound N (mg/m^3)
Oligotrophic lakes	2-20	20-200
Mesotrophic lakes	10-30	100-700
Eutrophic lakes	10-90	500-1300
Flowing waters	2-230	50-1100

These classifications do provide guidelines which are useful in applied limnology. However, they are not rigorous enough to permit trophic classification with a high degree of certainty. Vollenweider (1986) states that as a general rule, waters with total phosphorus concentrations in excess of 20 mg/m^3 may be regarded as in danger. Therefore, the use of absolute nutrient concentrations in the trophic classification of lakes must be done with care, and it is recommended that these be used only in conjunction with other trophic parameters.

The turnover or residence time of phosphorus might be considered as a useful measure of lake trophy. Data suggests that eutrophic lakes have long phosphorus turnover times, whereas short turnover times are characteristic of oligotrophic environments (Hayes, et al. 1952). Although, on a theoretical basis, turnover might provide a stable index of lake trophy, it does not seem likely that it will receive wide use. Since their measurement requires the use of radioactive phosphorus (^{32}P), phosphorus turnover times, although of theoretical interest, are not likely to become a routine measurement. This is especially true in larger lakes where the introduction of large amounts of ^{32}P is not desirable or practical.

Perhaps the most important contribution regarding the concentration of nutrients in relation to eutrophication is the nutrient loading concept of Vollenweider (1968). Although nutrient concentrations rather than nutrient supply will control the biomass of phytoplankton and macrophytes in a lake, nutrient loading is directly responsible for nutrient concentration. Vollenweider's early model (1968) for nutrient loading involved plotting the real total phosphorus loading against the mean depth on a log-log scale. From this plot, straight lines could be arbitrarily drawn separating the lakes into types: oligotrophic, mesotrophic, and eutrophic. The lower line separating oligotrophic and mesotrophic lakes was designated as the "permissible loading," since it represented the upper loading level as a function of mean depth that could occur without the lake deteriorating beyond the oligotrophic state. The upper line, separating mesotrophic and eutrophic lakes was designated " the critical loading," because, beyond this level, a lake would be characterized as eutrophic. The following table taken from Vollenweider gives these values:

Mean depth up to (m)	1. Permissible loading up to N (mg/1)	P (mg/1)	2. Critical loading in excess of N (mg/1)	P (mg/1)
5	1.0	0.07	2.0	0.13
10	1.5	0.10	3.0	0.20
50	4.0	0.25	8.0	0.50
100	6.0	0.40	12.0	0.80
150	7.5	0.50	15.0	1.00
200	9.0	0.60	18.0	1.20

This initial sample model was received by the scientific community with much enthusiasm, because, for lakes with phosphorus loading data available, the predicted trophic status in most cases closely matched the observed trophic status as described by other criteria of lake trophy: transparency (secchi disc depth), chlorophyll concentration, oxygen depletion in the hypolimnion, etc. However, Dillon (1975) criticized Vollenweider's model because it fails to consider lake flushing rates. Dillon suggests plotting L (1-R)/p against mean depth (z), where L is the phosphorus loading, R is the retention coefficient of phosphorus in the lake, and p is the hydraulic flushing rate. Dillion applied this phosphorus loading equation to two Ontario lakes with very different flushing rates. His calculations accurately predicted that the lake with low flushing rates would be almost identical to the lake with high flushing rates in terms of degree of eutrophy despite the fact that the lake with high flushing rates received a phosphorus load 20 times greater than that of the other lake. Vollenweider (1975) also recognized the importance of water renewal time and modified his simple loading vs. mean depth relationship to include the mean residence time of water (T_w). By plotting loading against z/T_w, Vollenweider arrived at a more realistic representation of phosphorus budgets for lakes. Dillon's equation is perhaps more representative because it includes both flushing rate and retention time in its calculation. Other factors not considered in the models of either Dillon or Vollenweider include the effects of internal loading and the extent of the shoreline and littoral area. The effects of internal loading are exemplified by the highly eutrophic Rotsee in Switzerland (Vollenweider 1976). Input-output calculations for phosphorus budgets failed to account for the very high concentrations of phosphorus in the lake. Vollenweider concluded that the phosphorus enriched sediments serve as a long term periodic source for large inputs of phosphorus. It seems likely that many lakes which have been eutrophic for some time will contain large reserves of phosphorus in their sediments. This is of considerable importance for lake restoration because it implies that mere reduction in phosphorus input will not always result in lower phosphorus concentrations within the lake, and that the sediments may supply phosphorus to keep the lake in a eutrophic state for years to come. Although phosphorus loading budgets require substantial information for their construction, they appear to be one of the most valuable techniques in the identification of the causes and solutions to eutrophication. However, as pointed out by Shapiro (1978), input-output models do not allow for highly accurate predictions of lake trophic state. If one takes the log-log plot of the relationship between nutrient loading and ambient concentrations of chlorophyll a (Carlson 1977) and plots this relationship on a linear scale, the correlation between the two is much less pronounced and variations of up to 500% in chlorophyll a concentration for a given loading rate can be shown. This indicates that lake productivity is not simply a direct function of nutrient loading, but that loading is merely a factor which sets an upper limit to productivity, and the expression of this potential for productivity may be modified within a given range by a number of other factors, especially biological factors which are often ignored.

Although concentrations of nutrient elements are almost universally recognized as indices of lake trophy, other elements may have value in this regard. Beeton (1965) used concentrations of sulfate, chloride, sodium, calcium, potassium, and total dissolved solids as indices of the eutrophication of the Great Lakes. Most of these ions are conservative water properties, and, especially in larger lakes, they fluctuate less on a seasonal scale than the various forms of inorganic nitrogen and phosphorus. Although there is considerable uncertainty about the role that many of these ions play in the production of organic matter, changes in the concentrations of these ions, as well as that of total dissolved solids, seem to be well correlated with other indices of lake trophy. A possible explanation for this may be that the increase in the concentration of these ions may parallel increases in phosphorus and nitrogen, both resulting from the activities of modern man. Their value as trophic indicators requires further study.

Phytoplankton Biomass

Although phytoplankton biomass is directly related to both nutrient concentration and lake trophic status, it is often not easy to characterize the trophic status of a lake on the basis of single measurements of algal biomass. This is largely due to the extreme variability encountered within a lake, both spatially and seasonally. Typically dimictic lakes show two annual pulses of phytoplankton biomass coinciding with spring and fall overturn. During summer thermal stratification the growth of the phytoplankton often depletes the available nutrients within the epilimnion, and hence biomass may drop to very low levels. Furthermore, although phytoplankton are rather uniformly distributed in the water column at the time of turnover, they are usually concentrated in the upper water during thermal stratification, largely due to the limitation of light. Light limitation is also a factor of great importance during winter ice cover, especially if the ice is covered with snow. Limitation by light is often the primary factor accounting for very low winter levels of phytoplankton, and this often occurs even when nutrient levels are relatively high. Therefore, the use of phytoplankton biomass as a measure of lake trophy must be based on data which takes both seasonal and spatial variations into account. Various methods have been used for collecting data on the biomass of planktonic algae. Net tows are not considered ideal because even the finest mesh nets do not capture much of the community. Often the nannoplankton fraction (organisms 50 u) may comprise more than 50% of the plankton. Various types of volumetric water samples (Kemmerer, Van Dorn, Friedinger, Nansen bottles, etc.) have been frequently used and have the advantage of allowing for the capture of the entire algal community. However, these devices have the disadvantage of obtaining discrete samples, and unless a very large series of samples is taken, the samples may not be representative of the average plankton densities in the lake. Phytoplankton distributions are often patchy and horizontally irregular, both on a large scale, that is, relative to the entire lake and also on a smaller scale, relative to the vortices of Langmuir circulation within the epilimnion. Variations in vertical distribution, especially during stratified periods, are caused by both the effects of temperature and light and are often of relatively great magnitude (Fee 1976, Brooks and Torke 1977). Representative samples are perhaps best obtained with integrated water samplers or pumps which take a continuous profile sample within the water column.

Various procedures are available for the estimation of the phytoplankton biomass. Direct counts under a high power microscope combined with conversions to cell weight or volume appear to be the best method, because they provide information not only of the quantity of plankton present, but also its quality, diversity, and composition. This method, however, is extremely time consuming and requires highly skilled personnel for the taxonomic identification of the algae present. Other available methods are more easily performed but provide information only on the quantity of algae present. A measurement of water turbidity or the ability of the sample to scatter light gives a relative measure of algal biomass, but this method is generally not accurate for the comparison of different lake communities unless it is calibrated by direct microscopic counts. Furthermore, suspended inorganic and organic particulate matter may introduce substantial errors. This is true not only for turbidity measurements made on bottled samples, but also for on-site turbidity measurements made with light source--photocell instruments and with the secchi disc. Secchi disc transparency has traditionally been used in limnology and is usually among the parameters measured in most lake studies, because the measurements are made with relative ease. Their usefulness, however, is severely limited by errors caused by both non-living seston and water color. In many lakes, it appears likely that secchi disc transparency may be virtually independent of chlorophyll a concentration and other measures of algal biomass (Lorenzen 1978). This casts some serious doubts about the trophic index of Carlson (1977), which is based on chlorophyll a--secchi disc relationships. Nevertheless, secchi disc measurements probably do, in most cases, allow for gross comparisons between lakes of very different productivity and should be continued, with recognition of the shortcomings inherent in the method. In the last decade, the Coulter counter and more sophisticated particle counters have been used to obtain estimates of algal biomass. For these devices, the principle of operation involves the generation of electronic pulses as particles suspended in a fluid pass through an electronic field. In the more sophisticated models, pulse height analyzers allow for the construction of particle size spectra because the strength of the pulse generated is proportional to the size of the particle. These instruments do not separate living algal cells from dead algae and detritus, which may often form a sizable fraction of the seston. Biomass may also be estimated from the dry weight of plankton samples. Wet weight is generally not measured because of the very small sample weights and the problem of separating weight contributions by internal vs. external water. Some authors have determined the ash free dry weight in order to estimate the carbon content which is usually equal to 40-60% of the ash free dry weight. Other biomass estimation procedures involve the assays of nitrogen, phosphorus, proteins, and other organic components of plankton organisms. Direct measurement of the carbon content can be done by wet oxidation or by combustion in oxygen. Both methods measure the carbon of inorganic seston as well. Estimates of biomass from ATP content or DNA content have the advantage of measuring only living particulate material. However, further studies are needed to establish a relationship between DNA and/or ATP content and biomass as determined by other procedures. Perhaps the most widely used procedure, other than direct microscopy, is pigment analysis. Although a wide variety of photosynthetic pigments are present in the various taxa of organisms, chlorophyll a is the most frequently measured because it is found in all autotrophic organisms. In this procedure the algae are separated from the water on 0.45 micron porosity millipore filters. The filters are then extracted in 90% acetone to obtain the sample. The concentration of chlorophyll a is determined directly either with a spectrophotometer or a fluorometer (Strickland and Parsons 1972). This technique has received considerable attention in recent years. It has been widely used, especially in this country. Chlorophyll a standards are available upon request from the Chicago EPA office. The use of these standards should permit reliable comparisons from lake to lake and region to region. A very recent development in this field is the flow-through portable fluorometer, which allows for direct on-site measurement of chlorophyll a concentration without the tedious process of extraction. In order to improve accuracy and precision, a flow-through fluorometer should, however, be calibrated with a series of extracted samples taken from the lake under study.

Despite the difficulties in obtaining average annual values for plankton densities, the measurement of phytoplankton biomass does qualify as a criterion for establishing lake trophic state, especially when used in conjunction with other trophic parameters. Vollenweider (1968) surveyed the literature and concluded that the following statements may be made:

1. Maximum plankton densities in ultra-oligotrophic lakes are lower than 1 cm^3/m^3.

2. Highly eutrophic lakes may more or less exceed a value of 10 cm^3/m^3.

3. Bodies of water having trophic states ranging from mesotrophic to eutrophic fall between these two limits; the transition point is at plankton densities of about 3-5 cm^3/m^3. It is, however, impossible to set precise limits for these densities.

The biomass of macrophytes has not yet received as much attention as that of phytoplankton. Usually percentage areal cover is calculated from aerial photographs as an indication of the relative contribution by macrophytes. This method is best calibrated by "ground truth" quadrant sampling and weighing, but this is not often done. It is obvious that in many bodies of water, macrophytes may play a major role in nutrient dynamics and constitute a major fraction of the autotrophic biomass. Furthermore, they often present a problem by themselves for water use. At the present time, few studies have attempted to estimate their role in eutrophication.

Primary Production

That the trophic state of a lake is reflected by the production of its autotrophic communities is obvious from the previous discussions. Many authors have treated primary production as if it were synonomous with lake trophic state. Certainly the two are very closely interrelated. Estimates of primary productivity in aquatic environments involve the measurement of one of the reactants or products in the photosynthetic reaction:

$$6CO_2 + 6H_2O \xrightarrow{\text{light}} C_6H_{12}O_6 + 6O_2$$

Usually, either the production of O_2 or the uptake of CO_2 are measured, but recently, Wetzel and McKinley (1977) measured the uptake of tritium-labeled H_2O to estimate algal photosynthetic rates. However, the use of ^{14}C-labeled bicarbonate has become the most widely accepted method in recent years for estimating lake plankton production.

Three approaches may be taken to measure primary production in the natural environment. First, measurements may be made directly on an isolated sample of the natural community. Light and dark bottles and other enclosure techniques for ascertaining rates of CO_2 uptake and O_2 evolution are the most commonly used examples of this approach. Secondly, measurements may be performed directly on the natural environment without the isolation of a portion of the community. Such methods take advantage of short term changes which are the result of overall community metabolism. Diurnal changes in O_2 concentration, pH and alkalinity have been used by some to yield estimates of production. Thirdly, production rates taking place over longer time periods can be measured. Measures of changes in biomass concentration, nutrient depletion, and silica depletion for diatoms are examples of such an approach. Hypolimnetic O_2 consumption and total CO_2 accumulation are other examples which have been discussed earlier in this paper.

Despite various limitations and errors, the enclosure or light-dark bottle technique has proved to be the most widely used and most valuable, especially the light-dark bottle ^{14}C labeled bicarbonate uptake technique proposed by Steeman-Nielsen (1952). This technique can be used in a wider range of productivity rates than the light-dark bottle methods for oxygen evolution. Furthermore, since the movement of carbon is fundamental to the consideration of metabolic processes, the uptake of carbon is, from this standpoint, one of the best parameters to measure. The standard technique for phytoplankton productivity is to suspend light and dark bottles from an anchored float or stationary vessel at a series of depths at which the samples in the bottles have been taken. Although this procedure does, perhaps, best approximate conditions of light and temperature within the lake, the production values measured may or may not be representative of the average productivity of the lake over longer time periods because these measurements will be influenced to a large extent by the quantity and quality of light available during the incubation period. Some refinement in these measurements may be obtained by incubating the samples within an artificially lighted enclosure (Fee 1976, Senft, et al. 1978a, 1978b). Such enclosures measure the capacity of the sample to carry on photosynthesis under a range of light regimes which are controlled. Temperature is also controlled and adjusted to natural conditions. Mathematical models have been developed to relate light conditions to maximum photosynthesis by the lake community, and these allow for the estimation of natural lake community productivity by monitoring ambient light conditions between sampling intervals. By using the incubation technique, the influence of light quality and quantity and temperature are controlled, and the photosynthetic rates measured reflect the biomass and species composition of the phytoplankton and their ability to carry on photosynthesis at the ambient nutrient concentrations in the sample enclosure. Because of the high variation in production rates caused by varying light levels and other factors, investigators have rarely attempted to correlate rates with lake trophic state. Vollenweider (1968) did make such an attempt and obtained a crude relationship by allowing for the effects of light extinction coefficients for the lakes he included in his comparison. However, it is apparent that further studies are needed to more clearly elucidate these relationships.

f. Indicator Organisms

Many species of organisms are restricted to particular environmental situations, in which the presence or absence of various factors allow for their existence. Ecologists use the terms "habitat" and "niche" to define the conditions which allow a particular species to thrive in a particular locality. To a large extent, the trophic state and all of the factors associated with it, such as nutrient concentration of the water organic components of the sediments, oxygen regime, etc., define the habitat and provide the niche requirements for the species of organisms which inhabit lakes. Lakes with different trophic states provide different habitats. For this reason indicator species have been used to characterize lake trophic states since the early foundation of the science of limnology.

In our region the effect of trophic state on lake species composition is somewhat confounded by the past faunal history of the lake. Relict boreal communities still exist in some of our northern lakes, even though trophic state conditions have changed enough to be suboptimal. The introduction of various species by the activities of man has further complicated the situation, making it difficult to separate effects of change in trophic state from those of competition and species interaction. Nevertheless, indicator species have definite value in characterizing lake trophic state.

Phytoplankton species associations have received much attention, since trophic-related changes are often obviously reflected by changes in the phytoplankton. Hutchinson (1967), utilizing the earlier classification of Naumann (1931), Jarenfelt (1952), and other authors, considered 13 lake types based on trophy and dominant phytoplankton types. Palmer (1962) distinguished algal species as being characteristic of clean and polluted flowing waters, and much of this classification can also be applied to lakes. The importance of blue-green algae in characterizing conditions of advanced eutrophy is apparent in both of these classifications.

Rawson (1956) characterized Canadian lake phytoplankton associations for oligotrophic and eutrophic lakes and noted that whereas oligotrophic lakes frequently exhibit large numbers of species (especially desmids), eutrophic lakes usually are dominated by a few very abundant species. Diversity indices, however, should be applied with care, since sample size and frequency and the influence of littoral species may give a misleading picture.

Many other groups of organisms have been utilized as indicators of lake trophic conditions, and a complete review of these will not be attempted here. Chironomid midge larvae have been among the most important indicator organisms since the time of Thienemann's studies in Germany. Stahl (1959) examined midge larvae head capsule microfossils in sediment cores from Myers Lake, Marshall County. He found that the oligotrophic indicator *Sergentia* was dominant in the lower strata, but was replaced in more recent strata by *Chironomus* and *Chaoborus*. Stahl attributed this change to severe O_2 depletion in the latter history of the lake's development. This change and its interpretation correspond well to changes reported by Thienemann and other authors. Sergentia is still found in James (Steuben County), Crooked (Whitley County), and Oliver (LaGrange County) Lakes, which retain some O_2 in the hypolimnion during summer stratification. Other Indiana lakes sampled had Chaoborus, Chironomus, or both, and were devoid of O_2 during stratification.

The replacement of cold-water salmonid fishes by warmwater tolerant fishes, such as centrarchids and cyprinids, is well known for many lakes suffering from culturally induced eutrophication. In Indiana the cisco (Coregonus artedii) is found in some northern lakes. At the time of Frey's survey (Frey 1955), cisco were still found in 41 lakes, having been erradicated from at least 4 lakes within historic times. Today the number of lakes containing cisco has probably declined to perhaps only 10 (R. Hollingsworth pers. comm.). In general the cisco lakes investigated by Frey had a thicker stratum of water with temperatures below 20°C and an oxygen content of 3 ppm or more greater than non-cisco lakes. Shallower cisco lakes tended to have an oxygen maximum in the thermocline. Cisco exist in Indiana as relict populations, left over from early postglacial times. Conditions in most Indiana lakes in which they are found are probably sub-optimal at best, and therefore cisco are extremely vulnerable to slight changes in lake trophic state.

Several difficulties are apparent when one considers using biological indicators for the trophic classification of lakes. Most data sets involving indicator species must be evaluated on the basis of particular species being either present or absent, making qualitative interpretations of such data difficult. Furthermore, the limits of tolerance for many potential indicator organisms are not well understood.

Diversity indices may be of value, but care must be taken to select a community for which diversity measures are appropriate. The community must contain a large enough number of species to make comparisons valid, and at least part of the community must be subject to changes in species composition under changing trophic conditions. From this standpoint, measures of the diversity of the phytoplankton community would have more value than, for example, of the crustacean zooplankton, where the number of species is typically low, and many species are quite tolerant of a wide range of trophic conditions. A problem in the interpretation of diversity values exists, because it is difficult to establish relationships between diversity measures and trophic state measures that are consistent from lake to lake. These relationships require further study.

Conclusions

Since the factors discussed in the preceeding pages will all have bearing on sound lake management decisions and practice, and since information on many of these factors is limited or lacking, efforts should be made to gather information on them, especially as management plans are developed for individual lakes.

In summary the following categories of information would be very useful in management policy formulation:

1. Type of lake origin and development history.

   a. Identification of natural lakes of unusual or unique origin will allow special consideration to be taken to preserve their natural features.
   b. Information on the nature of bedrocks, soils, and drainage basin characteristics will be useful in selecting protection and restoration techniques.

2. Morphometry

   Additional information (supplementary to what is presented in this report) may be useful in management and restoration policies and programs.

3. Hydrology

   Renewal times, flushing rates, and watershed dynamics all have important bearing on the curbing of nutrient inputs. The effects of watershed factors on water chemistry are also an important consideration.

4. Temperature cycles

   An understanding of thermal cycles, stratification and mixing is fundamental to dealing with the nutrient dynamics and productivity of lake systems.

5. Terrestrial and aquatic biological communities.

   a. Problem species, e.g., blue-green algae, macrophytes, rough fish, etc.
   b. Aesthetic features and areas requiring aesthetic enhancement.
   c. Naturally occurring species and communities requiring protection and special treatment.

In this report, lake trophic state has been estimated by use of a composite index developed by the ISBH. From the previous discussions, the following conclusions can be made regarding trophic state parameters and trophic state indices derived from them:

1. Lake trophic state can be ascertained by using any of several trophic state parameters.

2. Of the several parameters presented, it is difficult or perhaps impossible at the present time to regard any one parameter as being intrinsically the best parameter to measure for all lakes.

3. All trophic parameters may show considerable variation both seasonally and spatially, dependent on a variety of conditions, and therefore single samples may be more or less indicative of average conditions.

4. Limits or boundaries for trophic states (e.g., oligotrophic, mesotrophic, eutrophic, etc.) have not been established for all trophic parameters, nor is there universal agreement on the limits for any trophic parameter at this time.

5. Any index of trophic state utilizing several trophic parameters is likely to be more representative of actual lake conditions than an index based on a single parameter.

With these conclusions in mind, we have decided to use the trophic index developed by the ISBH in our analysis of the Indiana Lake Survey data, since this multiparameter index utilizes all of the information pertaining to lake trophic state obtained in the sampling program.

However, any additional information pertaining to the trophic condition of any lake being considered in lake protection or restoration should be considered in lake management decisions. Furthermore, as lake protection and restoration projects are implemented, trophic state should be monitored, so that the effectiveness of the project can be evaluated.

Part II. Analysis of the Indiana Lake Classification Program Data

The Indiana Lake Classification System was finalized in 1972 in accordance with Section 303(e) of Public Law 92-500, which requires that state program plans include a classification of publicly-owned freshwater lakes according to their trophic state along with an identification of corrective measures to restore the quality of problem lakes. Each lake was sampled at least once (a few were sampled more often) by ISBH biologists during the summer months (June to September) when the lakes were stratified over a five-year period. Since sampling was conducted only once for most lakes, it is to be expected that parameter values may vary somewhat in time from values reported for the lake on the sampling date. However, since several trophic parameters were measured, it is highly likely that the sampling data and the resulting ISBH Eutrophication Index identify the trophic state of the lakes within a reasonable range.

The ISBH Eutrophication Index was developed by Harold BonHomme with advice and consultation of other ISBH personnel. This index assigns points for lake trophic parameters to give scores ranging from 0 to 75. The index utilizes all of the trophic parameter information gathered during the sampling program, and allows for a wide distribution of scores for the lakes. The method of calculation for the ISBH index is given in Table 1. Chemical parameters for the index were scored using average sample concentrations in the water column. It is possible for a lake to accumulate 75 eutrophy points.

Data from the lake information sheets were transcribed and recorded onto a master data file on the Ball State Dec-10 computer system. Each individual sampling effort, whether an individual lake, an individual sampling site, or a different date, was entered as a unique case. For each case there are 306 variables. Each variable was recorded as a numerical entry; alpha-numeric information (e.g., lake, county, U.S.G.S. quadrangle names) are given preassigned codes. Missing information was recorded as the value "-9.0." In special cases where chemical information was listed as "less than" a particular value, that value was recorded as a negative (e.g., 0.01 is recorded as "-0.01"). All other values are positive.

Table 1. Calculation of the ISBH Lake Eutrophication Index

Parameter and Range			Eutrophy Points
I.	Total Phosphorus (ppm)		
	A.	At least 0.03	1
	B.	0.04 to 0.05	2
	C.	0.06 to 0.19	3
	D.	0.2 to 0.99	4
	E.	1.0 or more	5
II.	Soluble Phosphorus (ppm)		
	A.	At least 0.03	1
	B.	0.04 to 0.05	2
	C.	0.06 to 0.19	3
	D.	0.2 to 0.99	4
	E.	1.0 or more	5
III.	Organic Nitrogen (ppm)		
	A.	At least 0.5	1
	B.	0.6 to 0.8	2
	C.	0.9 to 1.9	3
	D.	2.0 or more	4
IV.	Nitrate (ppm)		
	A.	At least 0.3	1
	B.	0.4 to 0.8	2
	C.	0.9 to 1.9	3
	D.	2.0 or more	4
V.	Ammonia (ppm)		
	A.	At least 0.3	1
	B.	0.4 to 0.5	2
	C.	0.6 to 0.9	3
	D.	1.0 or more	4
VI.	Dissolved Oxygen		
		Percent Saturation at 5 feet from surface	
	A.	114% or less	0
	B.	115% to 119%	1
	C.	120% to 129%	2
	D.	130% to 149%	3
	E.	150% or more	4

VII.	Dissolved Oxygen		
		Percent of measured water column with at least 0.1 ppm dissolved oxygen	
	A.	28% or less	4
	B.	29% to 49%	3
	C.	50% to 65%	2
	D.	66% to 75%	1
	E.	76% to 100%	0
VIII.	Light Penetration		
		Secchi Disc	
	A.	Five feet or under	6
IX.	Light Transmission		
		Photocell	
		Percent of light transmission at a depth of 3 feet	
	A.	0 to 30%	4
	B.	31% to 50%	3
	C.	51% to 70%	2
	D.	71% and up	0
X.	Total Plankton per ml:		
		One vertical tow from a depth of 5 feet	
	A.	Less than 500 ml	0
	B.	500 to 1,000/ml	1
	C.	1,000 to 2,000/ml	2
	D.	2,000 to 3,000/ml	3
	E.	3,000 to 6,000/ml	4
	F.	6,000 to 10,000/ml	5
	G.	More than 10,000/ml	10
	H.	Blue-green dominance	5 additional points
		One vertical tow from a depth of 5 feet that includes the beginning of the thermocline	
	A.	Less than 1,000/ml	0
	B.	1,000 to 2,000/ml	1
	C.	2,000 to 5,000/ml	2
	D.	5,000 to 10,000/ml	3
	E.	10,000 to 20,000/ml	4
	F.	20,000 to 30,000/ml	5
	G.	30,000 or more	10
	H.	Blue-green dominance	5 additional points
	I.	Populations of 100,000 or more	5 additional points

Information from the computer data file was analyzed extensively using packaged statistical programs available on the Ball State University's Dec-10 system. Plotting and regression programs of the SPSS (Statistical Package for the Social Sciences) package were used to look for meaningful relationships among water quality parameters. Classification of the Indiana study lakes was based upon results of clustering analysis performed using a subroutine of the BMDP-77 (Biomedical Computer Program, P-series) statistical package. Both statistical packages provide for controlled selection of variables to be analyzed and are widely accepted statistical tools. In addition to the above statistical packages, special computer programs were developed for unique data analysis such as the ranking of surveyed lakes by water quality parameters and calculation of various trophic indices.

Results from analysis of the Indiana lake survey data have been placed into five major categories. These include: 1) the identification and location of each lake, 2) the ranking of each lake according to selected water quality parameters, 3) the relationships of various water quality parameters to one another, 4) an evaluation of Carlson's trophic state index for Indiana lakes, and 5) classification of Indiana lakes using cluster analysis technique. Each category is related to one another in the sense that results from each preceding category were used to help initiate the succeeding analysis.

A. Identification and location of lakes

Each lake surveyed in the Indiana Lake Survey Program was precisely and unambiguously located using USGS 7½ minute quadrangle maps. Legal descriptions including section, township, and range numbers and geographical location in degrees, minutes, and seconds of latitude and longitude were determined for each lake. In general, these represent locations at the geometric center of the lake. In some instances, more than one sampling site was survey for a lake; in these cases, each study site was located individually.

B. Ranking of Indiana lakes according to selected water quality parameters

The surveyed lakes were sorted and ranked according to selected water quality parameters using a computer program developed by H. Senft. With this program it is possible to sort the surveyed lakes in ascending or descending order by any of the 306 variables. The results of six such variable rankings are:

1. Size

The largest lake surveyed is Monroe Reservoir (10,750 acres). The largest natural lake surveyed is Lake Wawasee in Kosciusko County, which has a size of 3,060 acres. The smallest bodies of water sampled are only 1.0 acre in size. Of the 400 lakes for which lake area was recorded, 19 (5%) have an area greater than 1,000 acres, 15 (4%) are 500 to 1,000 acres, 41 (10%) are 200 to 499 acres, 215 (54%) have an area from 25 to 199 acres, and 110 (27%) are less than 25 acres in size. The size of each lake is presented in Appendix I.

2. Maximum Depth

The deepest lake surveyed is Tippecanoe Lake in Kosciusko County which has a maximum depth of 123 feet. The shallowest lakes had maximum depths of 6 feet or less. Of the 398 lakes for which depth data are available, 4 (1%) are deeper than 100 feet, 19 (5%) are from 75 to 100 feet deep, 60 (15%) are from 50 to 74 feet deep, 194 (49%) are over

25 but less than 50 feet deep, and 121 (30%) are less than 25 feet deep. The maximum depth of each lake is presented in Appendix I.

3. Mean Depth

The lake with the greatest mean depth is Shriner Lake in Whitley County (mean depth = 45.0 feet). The smallest mean depth (2.0 feet) is found in three lakes--Trinity Springs in Martin County, and South Clear and Mud Lakes in St. Joseph County. Of the 401 lakes for which mean depth is recorded, 9 (2%) have a mean depth of 40 feet or more, 46 (12%) have a mean depth from 25 to 39 feet, 126 (31%) have a mean depth from 15 to 24 feet, 199 (50%) have a mean depth from 5 to 14 feet, and 21 (5%) have a mean depth of less than 5 feet. The mean depth of each lake is listed in Appendix I.

4. Average Water Column Total Phosphorus

The average water column total phosphorus concentration for the surveyed lakes varied considerably, from a high of 3.80 mg/l in North Twin Lake, Monroe County, to values of less than 0.01 mg/l in several different lakes. Only seven out of 391 lakes (2%) have values of 0.50 mg/l or higher. There are 95 lakes (24%) with average water column total phosphorus levels between 0.10 and 0.50 mg/l, 80 lakes (20%) with values from 0.06 to 0.10 mg/l, 198 lakes (51%) with phosphorus levels less than 0.06 but greater than 0.01 mg/l, and 11 lakes (3%) with levels of 0.01 mg/l or less. Appendix I presents the average water column total phosphorus concentration for each lake.

5. Secchi Disc Depth

The clearest lake sampled was Saugany Lake in LaPorte County; the secchi disc depth recorded there was 31.8 feet. Several lakes had secchi disc depths less than 1.0 feet; the most notable is Cedar Lake, Lake County, which had a secchi depth of only 0.8 feet. Fifty-one lakes (13%) had secchi disc depths of 10.0 feet or more, 200 lakes (50%) had secchi depths between 5 and 10 feet, 144 lakes (36%) had secchi depths from 1 to less than 5 feet, and 5 lakes (1%) had secchi depths less than 1 foot. The secchi disc depths for each lake are presented in Appendix I.

6. ISBH Eutrophication Index

Two of the 401 lakes for which index values have been calculated have the maximum number of points--75; these are Charles Lake in Steuben County and Gilbert Lake in Marshall County. Saugany Lake in LaPorte County has the lowest index value--1. Forty-two lakes (10%) have index values of 60 or greater, 248 (62%) have values from 25 to 60, and 111 (28%) have values less than 25. The eutrophication index value for each lake is presented in Appendix I.

C. Relationships of various water quality parameters among Indiana lakes

Several water quality parameters that were sampled in the lake survey program were examined for significant intercorrelations. The water quality parameters investigated and the results of analyses are presented below:

1. average water column ammonia vs. average water column total phosphorus. No significant correlation--Figure 2.
2. average water column nitrate vs. average water column total phosphorus. No significant correlation--Figure 3.
3. log secchi disc depth vs. log epilimnetic total phosphorus. No significant correlation--Figure 4.
4. epilimnetic algal counts vs. epilimnetic total phosphorus. No significant correlation--Figure 5.
5. secchi disc depth vs. chlorophyll a concentrations for 27 Indiana lakes.

The relationship of secchi disc depth to chlorophyll a for Indiana lakes is similar to relationships described in the literature (Figure 6). A log-log transformation of the data (Figure 7) yields a significant correlation (r = -0.60) with a regression line of: Log secchi disc (m) = 0.56 - 0.45 log chlorophyll a (ug/l). It must be remembered that the theoretical relationship between secchi disc depth and chlorophyll a concentrations is not a simple one. Other factors, most notably water turbidity and color, may affect secchi disc visibility. Lorenzin (1978) reviews this subject in some detail. For general considerations, however, one could use the simple log-linear relationship above to obtain crude estimates of algal biomass.

D. Evaluation of Carlson's trophic state index for use in the classification of Indiana lakes

Carlson (1977) has developed a numerical trophic state index for lakes that is based upon empirically observed relationships between secchi disc transparency, chlorophyll, and total phosphorus. This index has been received with enthusiasm by many state and federal agencies since it represents a simple method for quantifying the trophic status of lakes. Recently, however, the validity of Carlson's index has been questioned (Lorenzin 1979, Megard, et al. 1979). Since the index is potentially misleading, a thorough evaluation should be conducted before it is used as the basis for lake management schemes in Indiana. We have evaluated Carlson's index using data from approximately 300 lakes in Indiana. Values of Carlson's trophic state index (TSI) were calculated based upon two different measures--secchi disc transparency and average water column total phosphorus. Figure 8 shows the relationship between Carlson's secchi disc TSI and the ISBH index for 300 Indiana lakes. The relationship is a poor one; $r^2 = 0.34$. There is a wide variation in TSI values for a given ISBH index score. Figure 9 shows the relationship of Carlson's phosphorus TSI and the ISBH index. This relationship is even

Figure 2. Average water column ammonia vs. average water column total phosphorus for 245 Indiana lakes.

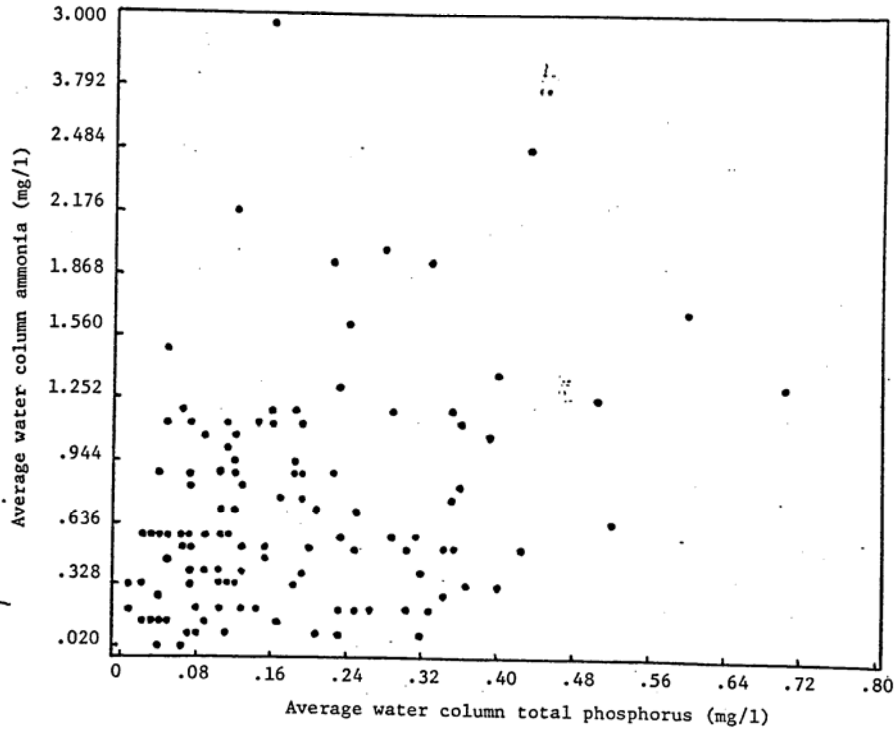


Figure 3. Average water column nitrate vs average water column total phosphorus for 124 Indiana lakes.

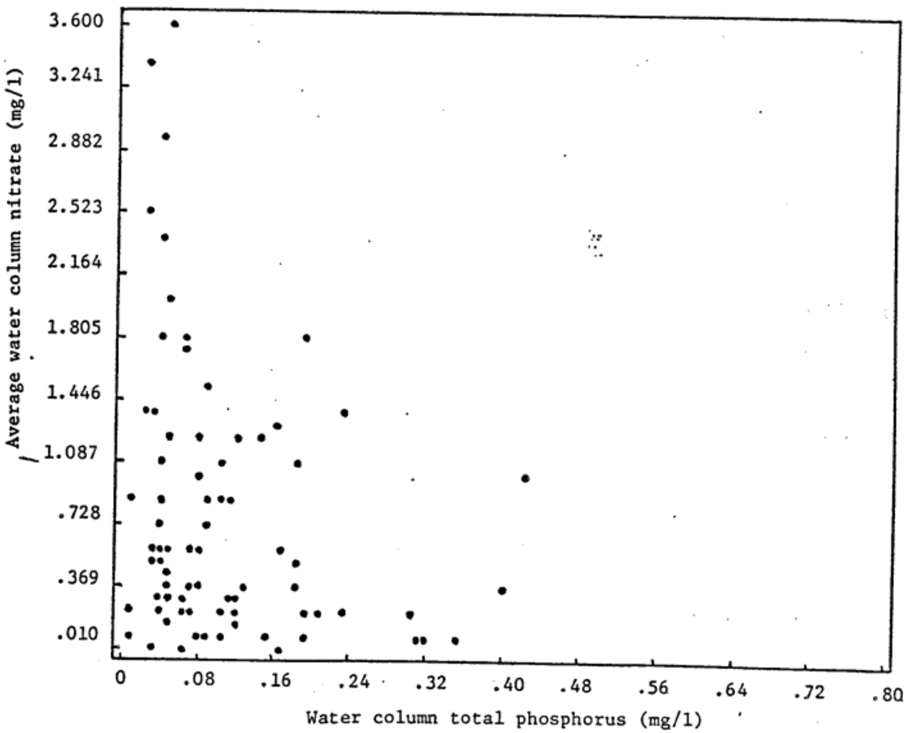


Figure 4. Log secchi disc depth vs. log epilimnetic total phosphorus for 137 Indiana lakes.

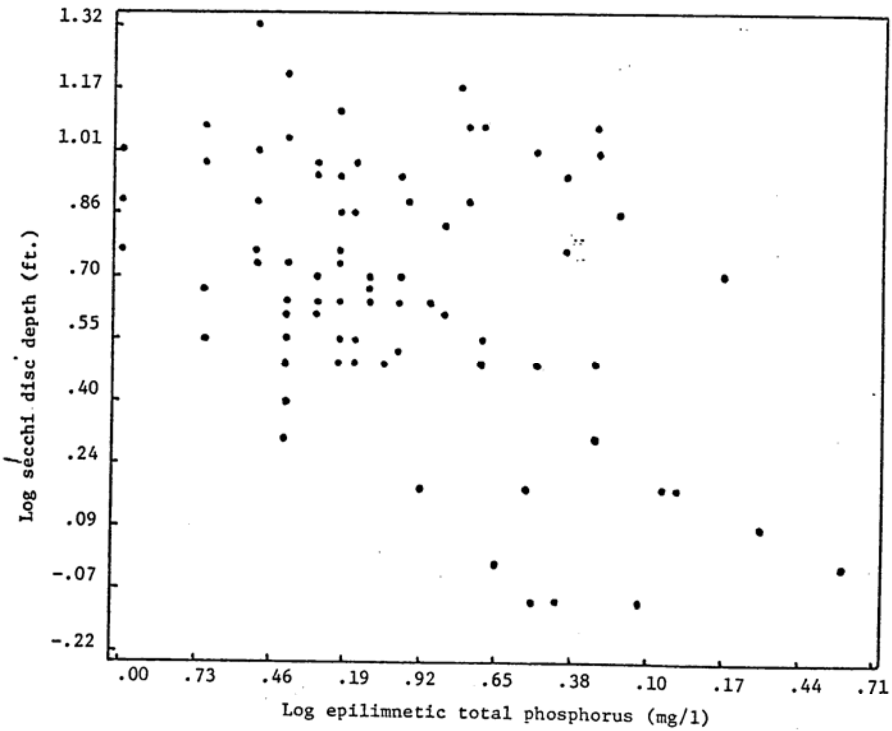


Figure 5. Epilimnetic algal counts vs. epilimnetic total phosphorus for 84 Indiana lakes.

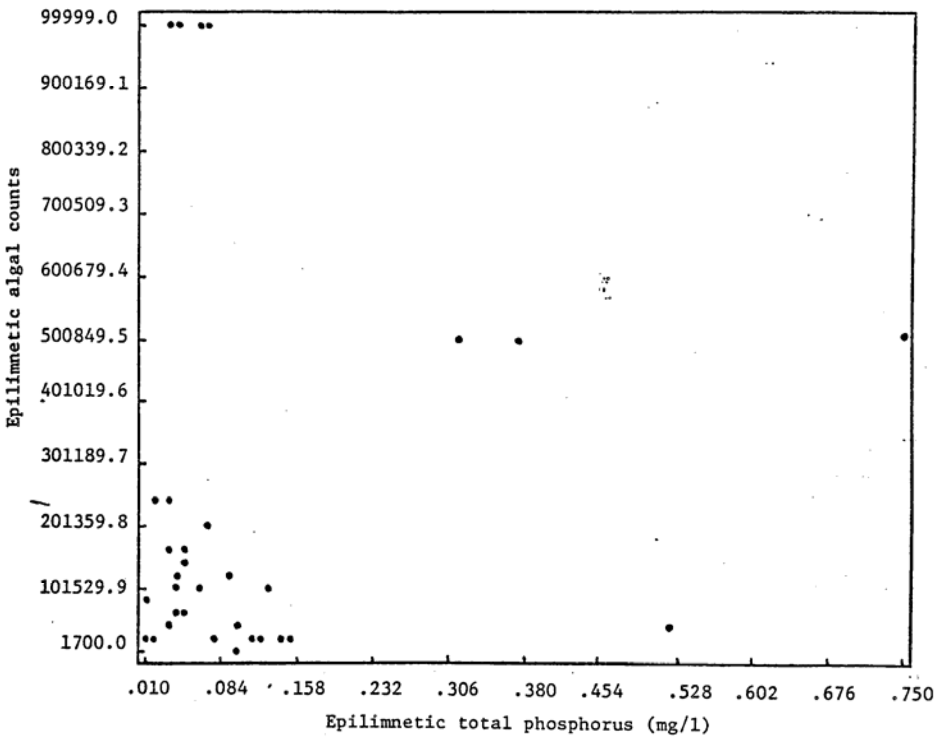


Figure 6. Secchi disc depth vs. chlorophyll a concentrations for 27 Indiana lakes.

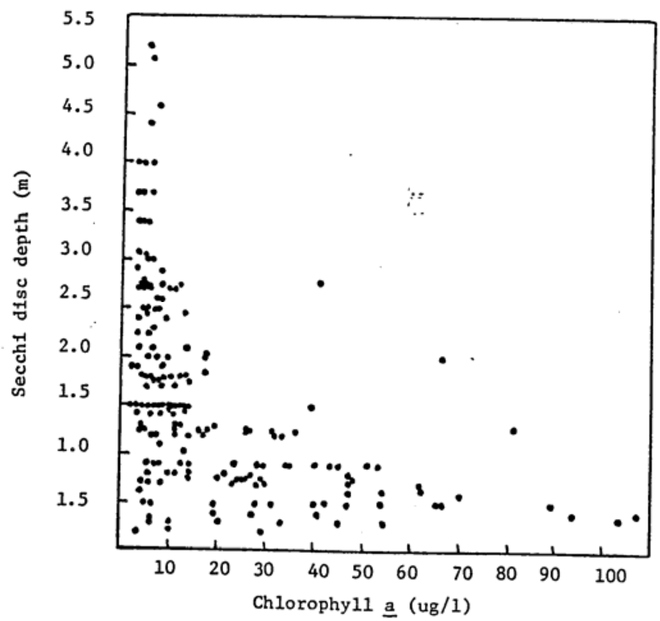
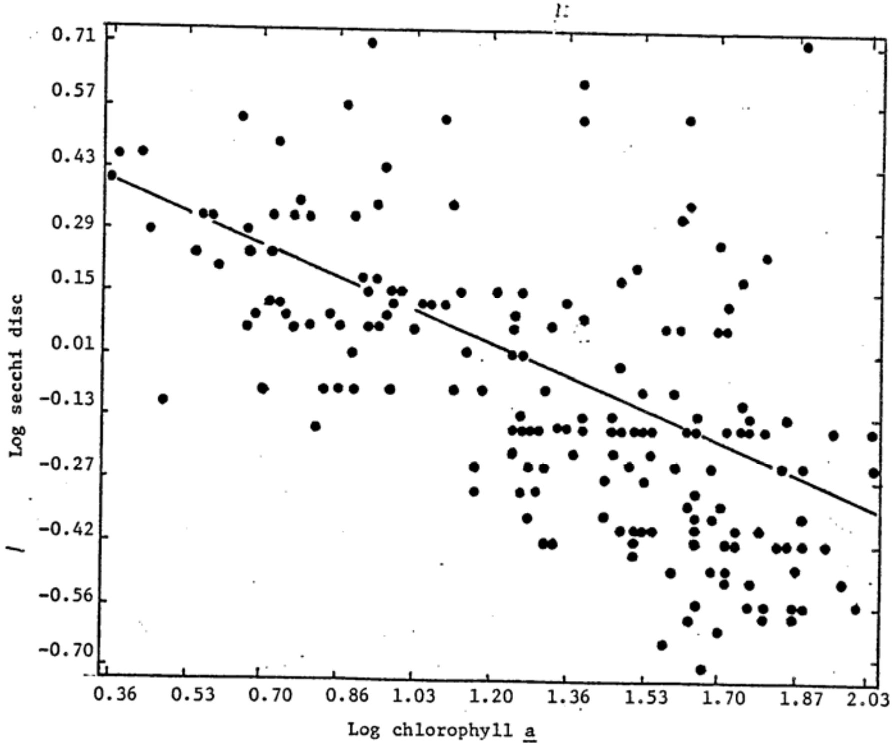


Figure 7. Log secchi disc depth vs. log chlorophyll a concentrations for 27 Indiana lakes.



poorer; r^2 in this case is only 0.21. Again, lakes with known ISBH eutrophication scores have vastly different TSI values. Lakes that rank near the top of the ISBH index often have low to medium TSI scores. As a final check on the usefulness of Carlson's index, we plotted TSI scores based on average water column total phosphorus vs. TSI scores based on secchi disc transparency for 237 Indiana lakes. Theoretically, this relationship should be close to unity. In Figure 10, however, one can see that the relationship is a very poor one; $r^2 = 0.14$. The TSI score for a particular lake varies considerably depending upon which water quality parameter is used in the calculation.

The above results cast serious doubt upon the usefulness of Carlson's trophic state index as a management tool for Indiana lakes. Although the ISBH index can be criticized, it is probably the best indicator of lake quality that the State of Indiana possesses. The total lack of correlation of the TSI (TP) and TSI (SD) indices indicates that for the Indiana Lake Classification Program data, Carlson's trophic state index is of very limited usefulness. We do not recommend its use by the ISBH in classifying Indiana lakes unless more reliable data is collected.

E. Classification of Indiana lakes based on trophic status

The following definitions and descriptions of lake classes are based on physical, biological, and chemical measurements made in the deepest basin(s) during summer thermal stratification. Visual observations and historical data are also considered. These lake classes should not be confused with lake management groups which will be discussed later in this report.

Table 1 explains the method of assigning eutrophy points to the data ranges of the ten diagnostic parameters. Each lake receives from zero to 75 total points, and the higher the point total, the higher the degree of eutrophy.

The study lakes are divided into three classes for broad classification and identification purposes. There is a fourth class which includes remnant lakes and oxbow lakes that cannot be accurately included with other lake types. Table 2 provides an inventory of the number and acres of lakes in each class.

Class One. Highest Quality, Least Eutrophic Lakes (0-25 Eutrophy Points)

Class One lakes are those which often exhibit some oligotrophic or mesotrophic characteristics. These lakes, rarely support concentrations of macrophytes or algae that could impair attainable lake uses, and chemical control programs are rarely necessary. These lakes frequently possess the following trophic characteristics:

1. Relatively low total P concentrations (0.03 mg/l or less as a water column average).

Figure 8. The relationship between Carlson's (1977) secchi disc TSI and the ISBH ranking for 300 Indiana lakes. Parameters for the fitted line (a = 41.3; b = 0.33) are from a least squares fit to the data.

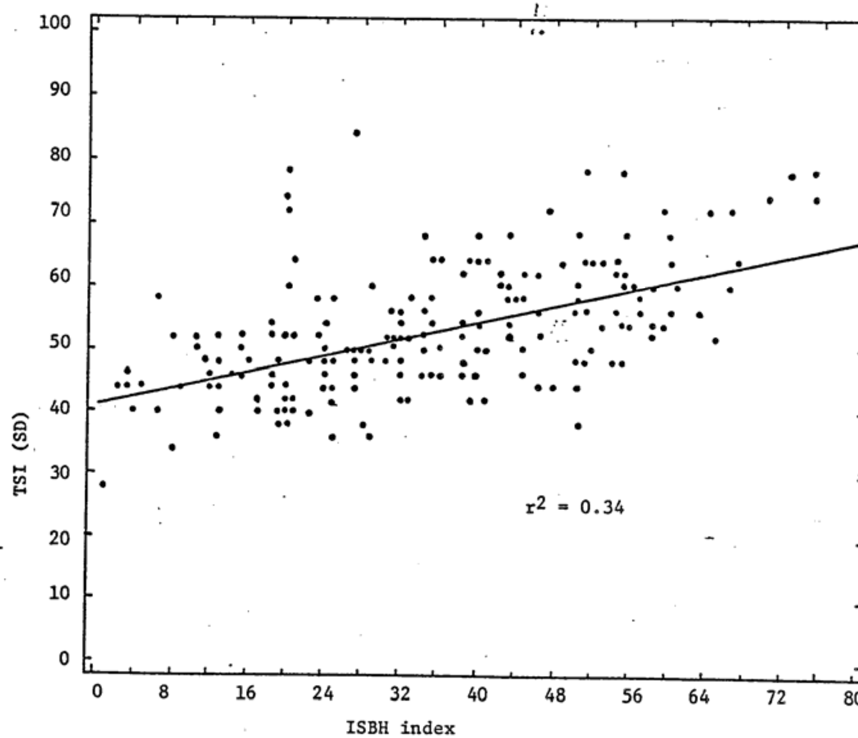


Figure 9. The relationship between Carlson's (1977) total phosphorus TSI and the ISBH eutrophication ranking for 224 Indiana lakes. Parameters for the fitted line (a = 51.3; b = 0.40) are from a least squares fit to the data.

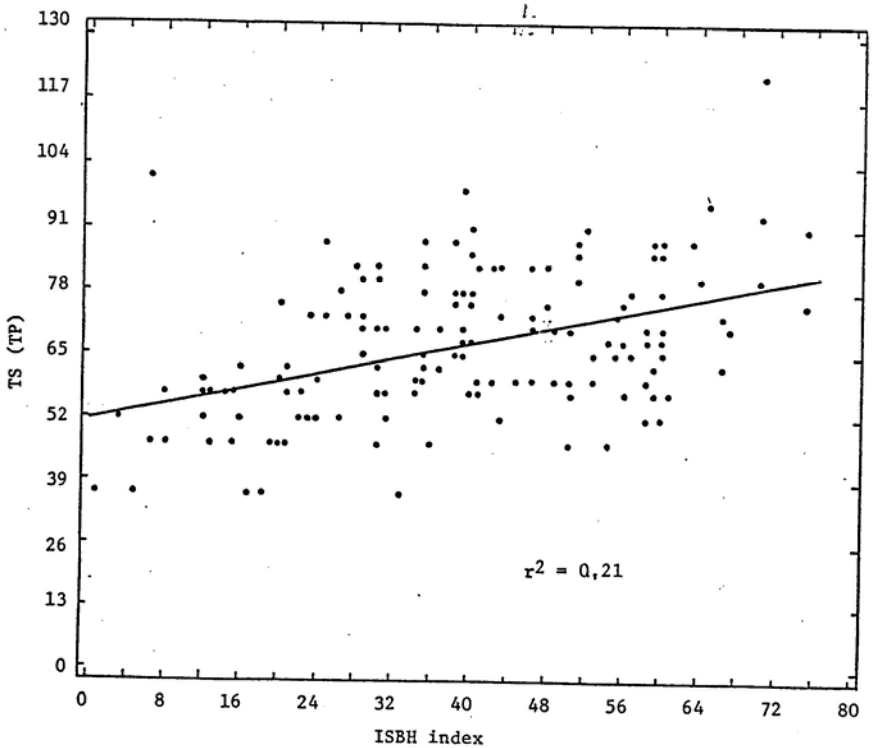
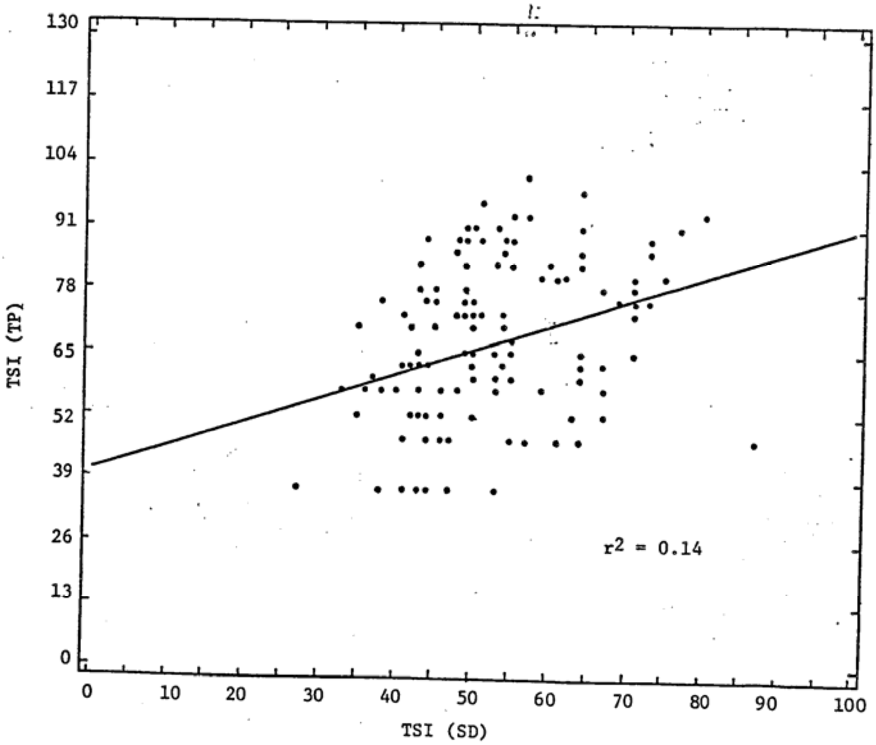


Figure 10. The relationship between Carlson's (1977) total phosphorus TSI and secchi disc TSI for 237 Indiana lakes. Parameters for the fitted line (a = 40.0; b = 0.51) are from a least squares fit to the data.



2. Relatively low TKN values (0.5 mg/l or less as a water column average).

3. At least 0.1 mg/l dissolved oxygen remaining at the bottom during periods of stratification.

4. Few blue-green algae blooms. Diatoms are usually dominant.

5. Few areas of extensive macrophyte development except in man-made channels.

6. Solar light values at a depth of three feet are often 75% to 100% of the surface value.

7. The lake often has a high deep water/shallow water ratio.

8. Summer thermal stratification is strong and well defined.

Class Two. Intermediate Quality, Intermediate Level Eutrophic Lakes. (26-50 Eutrophy Points)

Class Two lakes are usually productive and very slowly moving toward senescence. They are impacted by the activities of man, but trophic changes are usually subtle. In the absence of a chemical control program, they frequently support extensive concentrations of macrophytes and/or algae, but seldom to the extent that one or more attainable lake uses are significantly impaired. Class Two includes the majority of Indiana's natural lakes.

Class Two lakes commonly exhibit the following characteristics:

1. Total P concentrations of 0.04 to 0.06 mg/l as a water column average.

2. TKN values of 0.6 to 0.9 mg/l as a water column average.

3. Dissolved oxygen values are usually at 0.0 mg/l in the deeper waters of the hypolimnion during stratification.

4. Plankton blooms occur frequently during hot weather but these are not commonly of nuisance proportions. Blue-green species are commonly dominant, but often alternate with diatoms.

5. There are usually extensive, but non-problem, macrophyte concentrations in bays and littoral areas. Man-made channels and boat lanes usually have some degree of problems with the overproduction of macrophytes and/or algae.

6. Solar light values at a depth of three feet usually range from 30 to 50% of surface value.

Class Three. Lowest Quality Lakes, Advanced Eutrophic. (51 to 75 Eutrophy Points)

These lakes which, without a chemical control problem, always support extensive concentrations of aquatic weeds and algae during the summer. One or more lake uses are commonly impaired. Blue-green algae species are dominant, and they produce nuisance blooms of long duration during most summer months. Fish kills caused by oxygen depletion may occur during extended hot weather in summer or under ice cover in winter. Class Three lakes are usually highly productive and several are described as hypereutrophic.

Class Three lakes often exhibit the following characteristics:

1. Total P concentrations of 1.0 mg/l or more as a water column average.

2. TKN values of 2.0 mg/l or more as a water column average.

3. Dissolved oxygen concentrations often declining to 0.0 mg/l immediately beneath the first one or two feet of the thermocline. In hypereutrophic lakes, D.O. values may reach 15 to 20 mg/l or more on the surface and then decline to 0.0 mg/l only a few feet beneath the surface.

4. Solar light values at a depth of three feet may decline to 0% of surface values.

5. Nuisance blue-green algae blooms are common. Scums are formed on lake surfaces and littoral areas. Swimming may be impaired. There may be problems with both macrophytes and algae overproduction.

6. Bottom sediments composed largely of decomposing algae and macrophyte remains. Sediments are rich in nutrients and often form a flocculant layer on the lake bottom.

7. Many Class Three lakes have high shallow water/deep water ratios. Stratification may be weakly developed because of the shallow waters and winds often cause mixing of the nutrient rich hypolimnal waters.

Class Four Lakes. Remnant Natural Lakes and Oxbow Lakes.

These bodies of water, because of their small areas, general shallowness, natural origins, and advanced state of senescence cannot be accurately or realistically rated by using the Eutrophication Index. They may have comparatively low nutrient profiles because of nutrient uptake by macrophytes. Macrophytes sometimes dominate over plankton so that plankton counts are low, secchi disc measurements are high, solar light and dissolved oxygen are present to the bottom. These and other characteristics are common to Class One lakes. However, Class Four lakes are often filled with aquatic weeds or sediment and are well on the way to becoming wetlands. They are often small pieces of open water surrounded by marsh and some may actually be described as deep marsh. The Class Four remnant natural lakes are approaching the end of natural eutrophication, but may accumulate a widely varying number of eutrophication points.

Oxbow lakes are usually shallow, rich ponds that were formed when rivers cut through their old banks to new channels and left washouts and oxbow shaped bodies of water behind. These are usually rich in phosphorus and nitrogen, but algal production is low because of the turbidity produced by the rooting action of large numbers of bottom feeding fish and wind circulation. Macrophytes are usually also precluded by turbidity and periodic dessication when the oxbows shrink as the river falls during the dry season.

The majority of Class Four lakes are not large enough, deep enbugh, accessible, or aesthetically pleasing enough to be used for swimming, water skiing, boating, or building sites. The attainable uses of Class Four lakes are hunting, trapping, fishing, and wildlife propogation and refuge areas.

Table 2. Inventory of lake Classes
Natural Lakes

Class	Number	Acres
Class One	75	16,023
Class Two	144	13,867
Class Three	67	6,377
Class four	118 (Known Lakes)	2,448
Totals	404	38,715
	*Man Made Lakes	
Class One	44	31,157
Class Two	62	14,748
Class Three	44	2,813
Totals	150	48,718

*Patoka Reservoir, Potato Creek Reservoir, Merom Cooling Pond, and Sullivan Lake are not included.

F. Classification of Indiana lakes using cluster analysis

As a major focal point of this project, the lakes of Indiana were classified into similar categories using a cluster analysis procedure from the commercially available Biomedical Computer Program (P series) Statistical Package. Lakes were clustered according to three variables: 1) lake size (acres), 2) mean depth (ft.), and 3) ISBH index values. These three variables were mutually agreed upon by ISBH representatives. Lake size and mean depth were chosen since they provided the best available information on lake morphometry. The ISBH index scores were chosen as indicators of lake trophic state, since it was agreed that the index scores were, in our combined judgement, the most reliable measures of water quality for Indiana lakes. In the clustering algorithm, lakes were combined using an average distance or average linkage technique, where the distance measure used was the Euclidean distance between the standardized (z-scores) data points. Complete details of the clustering procedure can be found in Dixon (1977).

A total of 307 lakes was grouped into categories using the clustering procedure. Lakes were excluded from the analysis if they were smaller than 25 acres in size or if the value of any one of the three variables was missing. Results of the clustering procedure are summarized in Table 3. Lake groupings were established by visual inspection of the cluster diagram. In 1986, several lakes were added to the groupings using mean depth, lake size, and ISBH index value, but these were not run through the computer clustering procedure. In Appendix II, the lakes in each group are listed along with the values of each of the three variables.

Table 3 A summary of the lake groupings from cluster analysis

		Area (acres)	Mean Depth (feet)	Index
Group I		3,060-3,180	17.5-22.0	16-20
Group II				
	A	50-48	17.5-31.0	1-16
	B	40-1,034	31.2-45.0	3-25
	C	37-388	32.7-40.5	18-41
Group III		1,291-1,864	5.0-24.5	23-48
Group IV				
	A	26-385	2.0-7.3	50-65
	B	25-326	7.9-20.0	50-75
	C	150-575	5.0-14.0	62-75
	D	31-562	21.0-31.1	46-67
Group V		30-414	5.5-15.7	2-18
Group VI				
	A	25-421	15.0-27.0	13-39
	B	228-282	24.7-26.9	38-39
	C	802	20.7	31
Group VII				
	A	25-828	5.0-13.2	18-37
	B	28-551	12.2-19.6	27-54
	C	25-424	5.5-14.4	33-46

As seen from Table 3, seven major lake groups and twelve minor subgroups were identified. Separation of each of these clusters is somewhat variable; in several cases the delineations were less obvious and subjective choices had to be made. For the most part, however, the lakes separated into easily discernible clusters.

The Group I lakes are distinguished by their large size (over 3,000 acres). They include Lake Wawasee and the Mississinewa Reservoir. Monroe Reservoir, although not included in this analysis, would also belong to Group I.

Lakes in Group II are characterized by very large mean depths (31.2 feet or more) or intermediate mean depths (17.6-31 feet) and very low ISBH index scores (17 points). There are three distinguishable subgroups. Group II-A lakes are those lakes with the best water quality in the state (ISBH index scores 1-16) and intermediate mean depths (17.6-31). Lakes such as Stone Lake (LaPorte County), South Twin Lake (LaGrange County), and Cedar Lake (Whitley County) belong to this subgroup. Group II-B lakes also have the best water quality in the state (ISBH index scores 3-25), but tend to have greater mean depths (31.2-45 feet) than the II-A lakes. Tippecanoe Lake (Kosciusko County), Crooked Lake (Noble County), and Olin and Oliver Lakes (LaGrange County) typify this category. Those lakes belonging to Group II-C are separated by having large mean depths (32.7-40.5 feet) but generally higher index scores (18-41 points). Lakes in this group include Martin Lake (LaGrange County), Fish Lake (LaGrange County), and Dallas Lake (LaGrange County), among others.

The Group III lakes represent large bodies of water (1,291-1,864 acres), with somewhat intermediate mean depths (5-24.5 feet) and intermediate ISBH index scores (23-48 points). They are most closely related to the Group I lakes but are distinguished from those lakes by their higher index scores. Several reservoirs, Eagle Creek (Marion County), Geist (Marion County), and Morse (Hamilton County), as well as Dogwood Lake (Daviess County) and Maxinkuckee Lake (Marshall County) belong to this group.

The lakes with the poorest water quality belong to Group IV. They all have high ISBH index scores (50-75). There are four subgroups identified, although separation of one of these subgroups is tenuous. Group IV-A lakes are very shallow (2-7.3 feet mean depth). There are over 30 lakes in this group; representative ones include Chamberlain Lake (St. Joseph County), George Lake (Lake County), Loon Lake (Steuben County), and Green Lake (LaGrange County). Group IV-B lakes have mean depths from 7.9-20 feet. They include Hogback Lake (Steuben County), Silver Lake (Kosciusko County), and Pigeon Lake (Steuben County). Group IV-D lakes have mean depths from 21-31.1 feet. Yellow Creek Lake (Kosciusko County) and Big Otter (Steuben County) are two examples of this subgroup. Group IV-C lakes are not easily separated from the other subgroups, and no clear distinction is possible.

Group V lakes are distinguished from all other lakes by their good water quality (ISBH index scores 2-18) and generally shallow mean depths. The last factor separates these lakes from Group II-A lakes. Examples of Group V lakes include Crystal Lake (Kosciusko County), North Twin Lake (LaGrange County), and Bass Lake (St. Joseph County). Many remnant lakes and old river bend lakes listed in the Group V Management

Plan have high index scores. These high scores usually result from points given for physical characteristics rather than poor water quality. Attainable uses are seldom impaired by poor water quality in these lakes.

The remaining two major lake groups, Group VI and Group VII, contain those lakes which are intermediate between the other lakes. Group VI lakes have mean depths from 15-27 feet and ISBH index scores from 13-39. Group VII lakes are somewhat shallower than the Group VI lakes (mean depths from 5-19.6 feet), but have about the same range of trophic states (ISBH scores 18-54). The various subgroups of Groups VI and VII are separated on the basis of mean depths and index scores. Because lakes in these two major groups have mostly intermediate values for the three variables examined, their separation is less clear than for the other lakes. Appendix II lists lakes in each of the subgroups of Groups VI and VII.

The above cluster analysis results provide a realistic and useful classification of the Indiana lakes. The identified lake groupings represent lake types that closely resemble one another in terms of morphometry and water quality. This classification is limited, of course, by the data used to build it. Adding more variables to the classification scheme, however, would probably only result in more numerous lake groupings with fewer differences between the groups. The above scheme is a compromise between the ideal separation of lakes and simplicity. We feel the present lake groupings are sufficiently distinct so as to warrant their maintenance in a classification scheme. The classification scheme outlined here can be a very valuable tool for the state in managing its lakes. We suggest that the state adopt this scheme for its use.

Part III. A Review of Lake Rehabilitation and Protection Technology

Introductory Concepts

The purposes of lake classification for management are to identify problem lakes and to propose corrective action. Such actions require a knowledge of what the problems are and knowledge of what measures are available to solve them. Toward this end, a review of the current technology available for lake rehabilitation is undertaken in this section.

Although the causes of eutrophication and lake degradation have received substantial attention, there is great need for information and studies concerned with restoration and renewal of affected lakes. Such information is at the present time unfolding rapidly as numerous studies are completed and published. A compilation of lake rehabilitation experiences and technologies was undertaken by Dunst, et al. (1974). A review of measures for the restoration and enhancement of quality of freshwater lakes was compiled by the Office of Air and Water Programs of the U.S. Environmental Protection Agency (1973). The following discussion relies heavily upon these works.

Approaches to lake restoration can be placed into two categories: 1) procedures to limit production and sedimentation in lakes by curbing nutrient input, and 2) procedures to remove or manage the consequences of lake aging.

The objectives of limiting fertility in lakes are to reduce the excessive and undesirable growth of algae and rooted aquatic macrophytes and hence, by reducing their production, to reduce the rate of autochthonous sedimentation. It is generally agreed that the most desirable long term lake management approach is to reduce and control the input of nutrients, especially nitrogen and phosphorus. As discussed previously, these inputs may be diverse for a particular lake basin and, therefore, studies must be conducted to identify and locate nutrient sources for each lake in question.

A. Wastewater Treatment

For many lakes, domestic and industrial wastewaters constitute a major source of nutrients. Wastewater treatment is perhaps the most widely used technique for reducing the nutrient loads of wastewater effluents to rivers, streams and lakes. Indiana requires phosphorus removal for all dischargers to lakes or reservoirs or to their tributaries within 40 miles upstream if the discharge contains ten pounds or more of phosphorus per day. Additionally, phosphorus removal may be required of any discharger if it is necessary to protect water uses or to meet applicable water quality standards. Unfortunately, housing developments and communities on many lakes do not have sewer systems or wastewater treatment facilities. They rely on septic systems which, in many cases, have saturated the groundwater, thus causing a diffuse discharge of nutrients from the shore into the lake. Any septic system, by its very nature, must eventually saturate the soil of the septic field into which the wastewater is discharged. The time required for saturation to occur depends largely on the characteristics of the soil (Hook, et al. 1978). Since wastewater, either from point or diffuse sources, often constitutes a threat to water quality in lakes, a review of the basic technology and efficiency of wastewater treatment is presented here. This is based to a large extent on the paper by Rohlich and Uttormark (1972).

1. Primary sedimentation: This is the initial stage in most treatment processes. In some instances this and disinfection with chlorine constitute the total treatment. Usually, however, primary sedimentation is followed by the activated sludge or trickling filter process. Very little nutrient removal is accomplished by primary sedimentation alone.

2. Activated sludge process: This involves the aeration of biologically degradable wastes in the presence of microorganisms. After screening to remove grit, and primary sedimentation, the wastewater is mixed with recycled activated sludge in an aeration tank. After some time, the mixed liquor is channeled to a secondary sedimentation tank where the insoluble, cellular material is separated from the clarified effluent. Some of the settled sludge material is then recycled back to the aeration tank. Activated sludge processes have been reported

(Bunch 1969) to remove from 30-50% of the phosphorus. However, under special conditions some treatment plants have reported removals as high as 70-90% of the phosphorus. It has been observed that 30-40% of the nitrogen in domestic sewage is removed by conventional secondary treatment processes.

3. Trickling filter process: This procedure is similar to the activated sludge process. However, after primary sedimentation, the settled wastewater is allowed to trickle by gravity over a porous bed of gravel containing biologically activated growths on the surfaces. This is then followed by secondary sedimentation. Nutrient removal is, in general, poorer than that achieved with activated sludge processes. In recent years, wastewater treatment plant design and construction has gone over almost entirely to the activated sludge process.

Nutrient Removal System

Nutrient removal systems of various types may be used at any stage in the activated sludge process, but may only be used during primary sedimentation or as an additional tertiary stage with trickling filter processes. Various types of nutrient removal systems or tertiary treatment systems have been proposed. The major system types are reviewed here with an evaluation of their efficiency and economic feasibility.

1. Nitrogen Removal

a. Nitrogen Removal by Biological Growth

This is accomplished by the balancing of the carbon to nitrogen ratio in a conventional activated sludge process so that a higher percentage of the nitrogen is assimilated and bound in the microorganisms. Balance of the C/N ratio involves addition of carbohydrates or similar carbon sources. By adding glucose (Wuhrmann 1957) it is possible to raise the removal efficiency to about 70% for nitrogen. Although this procedure may be economically unfeasible in many situations, the use of effluents from certain food processing industries, such as sugar factories, can make this procedure relatively inexpensive in certain localities. Furthermore, the addition of supplementary carbon is also effective in the removal of phosphorus.

b. Microbial Denitrification

This is basically a two-step process involving extensive aeration to convert organic nitrogen and ammonium to nitrate-nitrogen, followed by anaerobic treatment to reduce nitrate to elemental nitrogen gas. The second phase of this process usually requires supplemental organic carbon (methanol, ethanol, acetone, or acetic acid) in order to assure complete denitrification. The N_2 gas and some nitrous oxide as well are removed by subsequent aeration. An alternative to using supplemental organic carbon sources has been proposed by Bringmann and Kuhn (1964), who suggest that raw sewage be used instead. The denitrification process requires organic hydrogen donors, and sufficient quantities of these are present in raw sewage, but these quantities are reduced by the aeration process. Bringmann and Kuhn's process is automatically controlled by the redox potential and, at the same time, by a partial vacuum. It requires a comparatively complicated flow technique. Perhaps further efficiency of the denitrification process could be achieved by reducing the degree of aeration during the nitrification stage. Bacterial nitrification in activated sludge occurs at oxygen concentrations as low as 1 mg O_2/l. In general, different types of microbial denitrification systems have achieved efficiencies varying from 50-80% nitrogen removal. It is important in the consideration of use of this process to determine elemental ratios of the raw sewage in relation to the nutrient concentration of the final effluent.

c. Ammonia Stripping

According to Rolich (1961), Wuhrmann (1964), and others, the remaining nitrogen in the final effluent of most activated sludge treatment plants is mostly ammonium. Ammonium ions in solution exist in equilibrium with ammonia gas and hydrogen ions. Therefore, by raising the pH to around 11, most of the ammonium ions are converted to ammonia gas which can be removed by air stripping. About 3,000 to 4,000 cubic meters of air is required to achieve 92-95% nitrogen removal for 1 m^3 of sewage. Stripping towers are required to facilitate air flow. Performance is reduced by cold weather because the wastewater is cooled by the air and solubility of ammonia in the water is increased. Another problem encountered is the formation of scale in the stripping towers. Although this process is highly efficient for removal of nitrogen, the cost of facility construction and operation may not be competitive with other methods. However, a great advantage of ammonia stripping systems is that they can be used in conjunction with phosphorus removal by precipitation with lime. Since phosphorus removal by lime addition requires a pH of 10 or above, ammonia stripping, which also requires a high pH, can be performed immediately afterwards.

d. Ion Exchange Processes

Ion exchange is a unit process in which ions of a given species are displaced from an insoluble exchange material by ions of a different species in solution. Nitrate ions are removed by anion exchange resins, whereas ammonium ions are removed by cation exchange resins. Both types of resins, however, have posed problems because of fouling by organic materials and poor ion selectivity. New anion and cation exchangers have recently been developed. The most useful of these ion exchange resins have been zeolites, which function as cation exchangers for the removal of ammonium. The zeolite currently favored for this use is clinoptilite (EPA-Technology Transfer 1974), which occurs naturally in several extensive deposits in the western United States. Studies of the process have been conducted by Battelle Northwest and the University of California. These studies demonstrated that average ammonia removal of 96% was obtained in treating wastewater with ammonia-nitrogen concentrations of about 20 mg/l. The ammonia exchange capacity of the clinoptilite was found to be nearly constant over the pH of 4.0 to 8.0 but diminished rapidly outside this range. Ammonia removals ranging from 93-97% were achieved with secondary effluents, advanced waste treatment effluents, and clarified raw sewage. The key point for the applicability of this process is the regeneration of the exchange resin and the method of handling the spent regenerate. Clinoptilite is regenerated by passing concentrated salt solutions through the exchange bed after the ammonia concentration has reached the maximum desired level. A mixture of lime and sodium chloride appears to be the best regenerant agent. The addition of sufficient lime raises the pH so that ammonium stripped from the bed during regeneration is converted to gaseous ammonia which can then be removed from the regenerant by air stripping. Other regenerant processes are available but pose problems of clogging of the cation bed, disposal of the regenerant, and high costs.

e. Breakpoint Chlorination

When chlorine is added to wastewater containing ammonium, the ammonium reacts with the hypochlorous acid formed to produce chloramines. Further addition of chlorine to the breakpoint converts the chloramines to nitrogen gas. Careful controls must be exercised in order to prevent the discharge of chloramines to the environment. Although breakpoint chlorination has advantages of relatively low capital cost, high efficiency, insensitivity to cold weather and the release of nitrogen as nitrogen gas, it has the disadvantages of adding a substantial quantity of dissolved solids to the effluent, relatively complex process controls, and the requirement of a downstream dechlorination process.

f. Miscellaneous Nitrogen Removal Processes

Ozonation will convert ammonium nitrogen to nitrate-nitrogen, but has the drawbacks of high cost and poor efficiency at low concentrations. The addition of ferrous sulfate reduces nitrate-nitrogen to nitrogen gas, but produces a chemical sludge which requires disposal. This may, however, become a feasible method if a low cost source of ferrous sulfate is available, as may be the case if used pickling liquor for iron castings can be obtained from nearby foundries. Algae harvesting involves nitrogen removal by harvesting algae grown in shallow ponds. Usually CO_2 and a carbon source (such as methanol) are required. Large land areas are also required, climatic conditions are a problem in many areas, and disposal of the algal sludge presents a further problem. Electrolysis uses an induced electric current and selective membranes to separate cations and anions in solution. Chemical precipitation, membrane clogging, and high costs of electric power are the major problems. In reverse osmosis, ions are separated by forcing wastewater through a cellulose acetate filter under high pressure. Membrane fouling and concentration polarization are major problems. Nitrate ions and certain other ions may pass through the membranes, limiting the usefulness of the process. Distillation as a nutrient removal process is only practical where a free source of waste heat is available. Scaling and disposal are also major problems. Land application involves spray irrigation of wastewater to produce usable farm crops. Large amounts of land are required and the method is not feasible in cold weather. Furthermore, traces of toxic substances present in wastewater may be concentrated in agricultural crops and pose a hazard to human health. Soil percolation removes ammonium but not nitrate ions and is disadvantageous in that the soil becomes saturated after a short time.

Phosphorus Removal

a. Biological Processes

The conventional activated sludge process typically removes 30-50% of the phosphorus present in wastewater. It has been suggested that the activated sludge process be operated in such a fashion as to stimulate the "luxury" uptake of phosphorus by microorganisms in the floc. This can be accomplished by maintaining anaerobic conditions throughout the process. Careful surveillance and control of the entire process is required. Therefore, it is perhaps best adapted to modern automated waste treatment plants in order to maintain low phosphorus concentrations in the effluent.

b. Chemical Processes

Chemical processes for phosphorus removal are typically what is meant by "tertiary treatment." These involve the addition of lime, aluminum sulfate (alum), sodium aluminate, or ferric salts to the secondary plant effluent. The addition of lime has been most widely used and results in the formation of an insoluable form of calcium phosphate, probably hydroxyapatite. Enough lime must be added to raise the pH to 10 or above in order to remove 90-95% of the phosphorus. Since ammonia stripping also requires a high pH, it can be used in conjunction with lime addition. This makes lime treatment an attractive process. The EPA (EPA-Technology Transfer 1976) reports on studies using various chemical processes for phosphorus removal in treatment plants of various designs and wastewater of various types. A computer program is provided for the economic and efficiency evaluation of the results of these studies. For instance, in one study, conducted at Butler, Indiana, a conventional primary plus trickling filter plant was adapted for tertiary treatment by the addition of lime and ferric chloride to wastewater that was quite hard (300 mg/l). Total phosphorus removal achieved was about 80%.

c. Biological-Chemical Processes

These involve a combination of the biological and chemical processes discussed previously. Chemicals may be added before, during or after any of the various unit processes in an activated sludge biological treatment system. The advantage of adding coagulating chemicals to the raw waste is that it promotes the removal of organic material in the primary clarifier while simultaneously removing a high percentage of the phosphorus. Disadvantages are the requirement of high chemical dosages and the production of greater volumes of sludge.

d. Other Processes

Several processes discussed in the section on nitrogen removal also apply to phosphorus removal. Ion exchange has been reported to remove 86-98% of the phosphorus present in wastewater; reverse osmosis removes 65-95%, distillation removes 90-98%, and land application removes 60-90% (Eliassen and Tchobanoglous 1969). A sorption process removes the phosphate from the waste as it passes through a sorption column. Nitric and other caustic acids are used in small quantities to regenerate the actived alumna in the column. The process removed 90% of the phosphate without changing the pH or the salt content of the treated wastewater (Yee 1965). This process is, however, still in the experimental stage.

B. Diversion

Diversion is the rerouting of waters outside of the lake's drainage basin. This may or may not be used in conjunction with wastewater treatment. Diversion without treatment has been severely criticized because it simply displaces the problem to another location. If, however, the new location is a river or stream, some benefits may be realized since rivers and streams have a higher self-cleansing potential than lakes. Some well known examples of this procedure include Lake Washington, Seattle, Washington (Edmondson 1970); the Madison Lakes (Mendota, Menona, Waubesa, and Kegonsa), Madison, Wisconsin (Sonzongni and Lee 1974); and the Chicago Sanitary Canal which diverts wastewater formerly discharged in Lake Michigan to the Illinois River. In essence, diversion can be a simple and economical solution to pollution problems which otherwise are not easily resolved.

C. Control of Incoming Sediments

In reservoirs, as well as some of the state's natural lakes, sedimentation is a major problem, restricting recreational use and, in many cases, greatly shortening the lifetime of the lake. Control measures at the present time include procedures to reduce sediment loss in the watershed (e.g., contour plowing, grade stabilization, grassed waterways, mulching, and others) and procedures to prevent eroded sediments from entering the lake (e.g., sediment basins and diversion basins). Detailed descriptions of sediment traps and other sediment control procedures are given by Thronson (1971). Many of these procedures are applicable to problems in Indiana's lakes and may be used in conjunction with nutrient abatement and in-lake rehabilitation projects. Where allochthonous sediments are a problem, these procedures should be given serious consideration.

D. In-Lake Rehabilitation Techniques

The objectives of various in-lake rehabilitation schemes are either to accelerate nutrient outflow or to prevent recycling of nutrients within the lake ecosystem. It must be emphasized that these techniques by themselves will usually provide only temporary relief from the effects of high nutrient levels unless they are used in combination with programs to reduce the input of nutrients to the lake. These techniques are directed at removing residual nutrients present in the water, sediment, or biota. Following is an evaluation of each of the techniques and an assessment of their usefulness in Indiana's lakes.

1. Dredging. At the present time, many people regard lake rehabilitation as being synonymous with dredging. Indeed many of the completed lake restoration projects in the U.S. have involved dredging the pond in the city park. In the past this has usually been done without any prior studies on conditions previous to dredging and often there were no follow-up studies. An evaluation of dredging as a lake restoration procedure was conducted by Pierce (1970), whose paper should be consulted for a detailed review of the subject. In general, dredging may be conducted by dry land or underwater methods. Dry land excavation by dragline or other earthmoving equipment may be practical if the lake can easily be dewatered. Larger lakes, however, will usually require underwater dredging by mechanical or cutterhead dredges. Selection of a method depends on the characteristics of the particular lake under construction.

In non-stratified, shallow lakes, nutrient regeneration from the sediments by wind generated mixing can be the major source of nutrients. Thus, dredging to expose a nutrient-poor layer can result in very significant reduction in nutrient concentrations. In deeper, thermally stratified lakes, however, dredging may not have this desired effect. Sedimentary phosphorus concentrations may only reflect the binding capacity of the sediments and not the nutrient concentration levels in the overlying waters. Furthermore, the dredging of lakes with large surface areas becomes impractical both from an economic and engineering standpoint. In certain shallow lakes, deepening of the lake basin by dredging so that a stable thermocline can form will usually reduce nutrient loading from the sediments. This technique is a beneficial and a widely used one for ponds and small lakes but is usually impractical for larger lakes. Deleterious side effects of dredging may outweigh its benefits in many situations. Dredging typically generates abnormal turbidity and can increase oxygen consumption by a factor of 10 or more. In many cases, dredging may lead to an immediate and massive fish kill. Usually, great increases in nutrient release are observed during the dredging operation. This is due to the mixing and suspension of sediment particles throughout the water column which allows for excessive release of nutrients and often results in a temporary but massive algal bloom. The buffering capacity of a lake to incoming nutrients may be lowered by removing fine grain sediments with high sorptive capacities, leaving coarse grain sediments with lower sorptive capacities. This may negate the benefits gained by removing nutrient rich sediments, especially if substantial nutrient amounts are still entering the lake. The benthic community may require some time to resettle dredged areas. This will have the effect of reducing fish production until the benthic community can recover. Recovery in some cases may require several years.

2. Drawdown and Sediment Consolidation. The water content of organic rich sediments in eutrophic lakes frequently exceeds 90% by volume. Consolidation of flocculent sediments by dessication is largely

irreversable and results in a deepening of the lake basin and an increase in lake volume (Smith, et al. 1972). Nutrient regeneration from the sediments is supposedly decreased by the physical stabilization of the upper flocculent sediment zone. However, it should be noted that drawdown and dry fallowing with subsequent reflooding is a frequently used technique in fish culture ponds for increasing productivity. Because dessication apparently accelerates microbial conversion of organic forms of nutrients to inorganic forms, higher algal and fish production can be achieved. In lakes, this effect is probably only temporary, and it seems likely that productivity would decline as the turnover of lake water proceeds and biological uptake and resedimentation of nutrients takes place. However, the results of studies on lake sediment consolidation are variable. Lake drawdown has also been used with some success as an aquatic vegetation control measure (Beard 1973).

The most detailed studies on lake drawdown as a method for improving water quality were conducted by Fox, et al. (1977) on the sediments of Lake Apopka, Florida. Their studies involved experiments on the effect of dessication on both sediment consolidation and sediment nutrient regeneration in the laboratory. Such pre-drawdown studies are to be recommended. These can be easily performed in aquaria or other containers, and can provide valuable information on the amounts of both sediment consolidation and sediment nutrient regeneration which can be expected for a particular lake.

3. Chemical Treatment for Nutrient Inactivation and/or Precipitation. The intent of these procedures is to change the form of nutrients to make them unavailable to plants, remove nutrients from the photic zone, and prevent release and recycling of nutrients from the sediments. Much of the technology in such procedures is borrowed from wastewater treatment practices. The addition of metal ions, using iron, aluminum, and calcium compounds, has been attempted with varying success. The formation of hydroxide precipitated by ions, such as Al^{+++} or Fe^{+++}, may create a pH problem in relatively unbuffered waters. When using Al^{+++}, this difficulty can be eliminated by adding a proper ratio of Al as alum to that added as aluminate. Other materials which have been tested as precipitants or sorption agents include ion exchange resins, zeolites, polyelectrolytes, flyash, powdered cement, and clay. Fitzgerald (1970) has recommended the use of aerobic resuspended lake sediments for phosphorus removal. This assumes that the equilibrium phosphate concentration for the sediments is well below the concentration measured in the water. Such a treatment would have the advantage of not adding unnatural solid materials to the lake. However, it should be emphasized that the effects of lake morphology, climatic conditions, thermal structure of lakes, and seasonal changes in specific nutrient forms and quantities may have substantial effects on these procedures and need to be further studied. A detailed study on the effects of alum treatment on lake nutrient conditions was performed by Peterson, et al. (1973).

4. Lake Bottom Sealing. In many instances, it may be more feasible to prevent sediment nutrient release with bottom coverings rather than by dredging or drawdown. In addition, some coverings can

inhibit macrophyte growth, provide erosion control, and reduce water loss. Polyethylene sheets covered with sand or gravel have been widely used as a bottom covering in ponds. Other bottom coverings include sand, flyash, clays, hydrous metal oxides, and certain gels. The sorptive capacity of sand and clay for phosphorus is very low. Therefore, the use of a chemical coagulant may be necessary to improve the nutrient uptake capacity of the new sediments. The use of flyash and hydrous metal oxides provides a strong sorbtive capacity for phosphate as well as a physical layer to retard transfer of nutrients. The following questions as yet remain unsolved. How permanent is the treatment? Will the sealant become disrupted by lake mixing or the burrowing activities of benthic organisms? What affects do these sealants have on benthic organisms and fish spawning success?

5. Selective Discharge. This technique permits the release of anaerobic, nutrient rich waters from the hypolmnion of the lake. This is most easily done in lakes with an outlet and has been widely used in reservoirs. In some reservoirs the pipe extends down the face of the dam into the downstream channel and operates as a siphon. The major objective is to improve dissolved oxygen concentrations near the bottom and increase the nutrient output from the lake. Although selective discharge has not achieved satisfactory levels of dissolved oxygen near the bottom in all cases, the removal of anaerobic water has been beneficial in most. Removal of colder bottom water does have the effect of increasing the overall lake temperature, and thus decreases the solubility of oxygen in the water. This, however, is usually offset by the increase in dissolved oxygen content in the replacement waters. Serious problems often result in the outflow stream due to the introduction of anaerobic nutrient-rich water. As this becomes oxygenated, a precipitant floc formed by the oxidation of dissolved iron will collect on the stream bottom and smother the benthic invertebrates and fish spawning areas in the outflow stream. Because this technique is largely concerned with improving dissolved oxygen conditions in the lake or reservoir in question, it is usually employed for the improvement of fish habitat and fish production. However, at this time, no evidence exists which demonstrates a positive effect on the fish community, although most studies have been short term in nature and perhaps inconclusive for this reason.

6. Dilution/Flushing. Dilution/flushing has been attempted in order to alleviate excessive algal and macrophyte growth by reducing nutrient levels within the lake. This is accomplished by replacing nutrient-rich water with nutrient-poor water and hence removing nutrients contained in the phytoplankton as well as those dissolved in the water. One method involves pumping water out of the lake to permit increased inflow of nutrient-poor ground water. This technique has only been tried once, in Snake Lake, Wisconsin (Born, et al. 1973), where only temporary effects were achieved. More often nutrient-poor surface waters are re-routed into the lake. This has been shown in several instances to be effective when combined with dredging. In several cases, nuisance blue-green algae blooms were eliminated. An important limitation to this technique is that the dilution water must contain substantially less nutrients than the lake water. Therefore, economic considerations and logistics limit this procedure to use in lakes where

a low nutrient water supply is in close proximity. Leaching of nutrients from the sediments and introduction of nutrients from the watershed may rapidly negate the effects of dilution/flushing if these nutrient sources are not addressed. Dredging is recommended, but it may by that repeated dilution/flushing over several years time may by itself deplete the sediment nutrients. Lake morphology and hydrodynamics are important considerations in locating the inflow to achieve maximum results. In Indiana, the use of dilution/flushing as a lake restoration technique probably has quite limited applicability because of the scarcity of low nutrient water supplies.

7. Aeration and/or Circulation. Circulation and aeration by mechanical means are common techniques used to improve the dissolved oxygen conditions of lakes and ponds for fishery or water quality purposes. No permanent changes are affected, and very few aeration projects have actually demonstrated a desirable fish population response. However, aeration does increase the rate of oxidation and decomposition of bottom sediments and organic matter in the water column. One would also suppose that aeration should promote the sorption of phosphorus by the hydrous oxides of iron and manganese (Mortimer 1941). The effects of aeration on other segments of the lake's biota, particularly the phytoplankton and zooplankton, requires more study. Two types of aeration techniques, total and hypolimnetic, have been commonly used. In total aeration, cold hypolimnetic water is pumped or air lifted to the surface. This usually removes any traces of thermal stratification, and in some instances, the entire lake may reach the mean epilimnetic summer temperature. Hypolimnetic aeration does not disrupt thermal stratification. In this technique, water is air lifted to a floating box and then allowed to flow by gravity through pipes back to the hypolimnion. Total aeration can completely eliminate cold water fish habitat. Furthermore, cold hypolimnetic water is preferred by municipal and industrial water supplies. Hypolimnetic aeration does not disrupt thermal stratification, but, because oxygen transfer is limited to the bubble water interface in most hypolimnetic aerators, oxygenation is slower than by total aeration techniques. Aeration as a lake management technique is discussed in detail by Smith, et al. (1975), and Lorenzen and Fast (1977).

8. Biotic Harvesting. Biotic harvesting involves the removal of nutrients by removing organisms in which these are concentrated. The removal of algae with microstrainers has been attempted in only one instance, in Clear Lake, California. This proved to be ineffective because of the time involved and problems with clogging of the strainers. The removal of aquatic macrophytes is a widely used technique in the United States. It is usually performed for cosmetic purposes, but nutrients are obviously removed. However, the effectiveness and economics of macrophyte cutting as a nutrient removal technique needs further study. Some people tend to regard it as a management procedure equivalent to lawnmowing. Cutting aquatic weeds without removing them merely increases the problem. Many aquatic macrophytes are capable of reproducing by vegetative means. Cutting without removal provides huge numbers of new potential plants. Another problem is the disposal of the cut plants. However, some studies have been made on their utilization for various purposes (Little 1968).

The removal of fish is a widespread technique carried out for fish management purposes, either to increase the growth of slow-growing but desirable fish by removing part of the population or to decrease the population of undesirable species in order to favor expansion of desirable species. The removal of carp (Cyprinus carpio) have been undertaken in many places throughout the country not only for fisheries management, but also to promote better water quality since the bottom grubbing activities of this fish increase turbidity and promote resuspension of nutrients from the sediments. Fish removal as a nutrient removal technique has not been thoroughly studied, and the data are inconclusive. This may be a valuable tool for nutrient removal when used in conjunction with other techniques. Other techniques previously discussed may result in the removal of organisms. Dilution/flushing may accomplish a physical washout of phytoplankton and has, in some instances, been used to remove nuisance algal blooms. Water level fluctuations and partial drawdown are used, especially in reservoirs, to control aquatic macrophytes, although actual removal of the macrophytes does not occur.

9. Chemical Controls. Various chemical algicides, herbicides, and pesticides have been and are used to control nuisance algae, macrophytes, and fish. Although the application of chemicals has become a common and widespread practice, no permanent effects are achieved. Nutrients contained in the organisms are not removed, and, typically, the treatment is repeated on a regular basis. The long-term effects of these chemicals and their fate in aquatic ecosystems present a potential danger which requires further study.

Part IV. A Recommended Management Plan for Indiana Lakes

In the effort to deal with a multitude of local and regional lake management problems, the Indiana Department of Environmental Management (DEM) is faced with the task of developing a wide-ranging lake management program. As part of this program, the DEM must establish priorities and procedures for alleviating lake water quality problems. In developing this plan, the ISBH initiated a lake survey program to collect baseline data on the water quality of most of the lakes in the State. This data was placed on computer tapes and analyzed; the results have been presented in Part II of this report. In this section, the results are applied to formulate a broad management plan for the lakes of Indiana.

The proposed plan is based upon the data supplied to us by the ISBH. The scope of the plan is defined by the available data. The plan establishes broad management categories, which serve as guidelines for initial policy decisions. Specific management decisions for individual lakes must be substantiated by further data collection and planning.

The management plan is based on the seven major lake groupings from the cluster analysis (Part II). These groupings and their associated subgroupings contain lakes which are morphometrically and trophically similar. These groupings provide a natural framework for the lake management plan. This plan is presented on the following pages.

Management Plan for Lake Groups

Group I

1. Wastewater treatment

   a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
   b. Septic tank maintenance programs.

2. Land use practice and watershed management

   a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.
   b. Protection of watershed wetland areas.
   c. Erosion control.
   d. Zoning and development regulation.

Because of the large surface areas and relatively good water quality, no restoration techniques are recommended. Curbing nutrient inputs from the immediate shoreline and the entire watershed is the primary management strategy.

Group II A and Group II B

1. Government or private protection

   a. Acquisition of shoreland.
   b. Restricted shoreland development and use.
   c. Restricted recreational use.
   d. Maintenance of existing aesthetic qualities.

2. Educational programs for lake and area residents to increase awareness of the natural resource value of these lakes

3. Maintenance of water quality

   a. Wastewater treatment, including phosphorus removal at many plants.
   b. Land use control in watershed.
   c. Protection of watershed wetland areas.

Group II C

1. Wastewater treatment

   a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
   b. Septic tank maintenance programs.

2. Land use practice and watershed management

   a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.

b. Protection of watershed wetland areas.
c. Erosion control.
d. Zoning and development regulation.

3. Restoration

a. Nutrient inactivation.
b. Selective discharge.
c. Macrophyte harvesting.
d. Chemical controls (algicides).

Groups II A and II B are fairly similar, except for mean depth, and contain some of the best examples of relatively undisturbed natural lakes in the state. The management priority for these lakes is the protection and maintenance of their present water quality and natural features. Group II C differs from Groups II A and II B in that some degradation of water quality has occurred. Management strategy for these lakes focuses upon improvement of water quality by curbing nutrient inputs. For some lakes in this subgroup, nutrient inactivation and/or selective discharge restoration techniques may be advisable.

Group III

1. Wastewater treatment

a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
b. Septic tank maintenance programs.

2. Land use practice and watershed management

a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.
b. Protection of watershed wetland areas.
c. Erosion control.
d. Zoning and development regulation.

3. Restoration

a. Macrophyte harvesting.
b. Sediment consolidation by drawdown.

Group III consists of large shallow lakes exhibiting eutrophic characteristics. Many of these lakes may be naturally eutrophic for morphometric reasons. For these lakes, management priority is to prevent further degradation by curbing nutrient inputs. For some lakes with more severe problems, the most promising restoration techniques would be macrophyte harvesting and sediment consolidation by complete or partial drawdown.

Group IV (entire group)

1. Restoration

    a. Aeration and/or circulation.
    b. Chemical controls (algicides).
    c. Macrophyte harvesting.
    d. Nutrient inactivation.
    e. Sediment consolidation by drawdown.
    f. Dredging.
    g. Lake bottom sealing.
    h. Selective discharge.
    i. Dilution/flushing.
    j. Various combinations of above restoration techniques.

2. Wastewater treatment

    a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
    b. Septic tank maintenance program.
    c. Diversion.
    d. Nutrient traps (wetland areas).

3. Land use practice and watershed management

    a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.
    b. Protection of watershed wetland areas.
    c. Erosion control.
    d. Zoning and development regulation.

Group IV contains most of the problem lakes in the state. The majority of these lakes have such severe water quality problems that recreational use may be impaired. Management priority for these lakes is to improve water quality as quickly as possible through restoration and nutrient abatement programs. The four subgroups are delineated by area and mean depth. Specific restoration techniques for an individual lake are dependent upon these factors. For example, because of shallow mean depths, most lakes in Group IV A may be restored by dredging, bottom sealing, or sediment consolidation. Because of greater mean depth, most lakes in Group IV D would probably be better restored by selective discharge, and/or nutrient inactivation. Although restoration is the major priority, this must be accompanied by curbing future nutrient inputs in order to achieve long-term improvement.

Group V

1. Government or private protection

    a. Acquisition of shoreland.
    b. Restricted shoreland development and use.
    c. Restricted recreational use.
    d. Maintenance of existing aesthetic qualities.

2. Educational programs for lake and area residents to increase awareness of the natural resource value of these lakes

3. Maintenance of water quality

   a. Wastewater treatment, including phosphorus removal at many of these plants.
   b. Land use control in watershed.
   c. Protection of watershed wetland areas.

Group V consists of shallow lakes with high water quality. Some of these lakes occupy former gravel pits, which accounts for their good water quality. Others are natural lakes which have received limited impact by man. Management priorities for Group V lakes stress maintenance of present conditions. The desirability and degree of state protection should be dictated by the natural and aesthetic values of the lake in questions. Because of shallow depths, the degree of protection needed for these lakes is probably greater than for those in Groups II A and II B. Remnant lakes and old river bed lakes which may be benefited by the Group V Management Plan often have high indices. These high scores usually result from points accumulated by physical characteristics rather than poor water quality.

Group VI

1. Wastewater treatment

   a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
   b. Septic tank maintenance programs.

2. Land use practice and watershed management

   a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.
   b. Protection of watershed wetland areas.
   c. Erosion control.
   d. Zoning and development regulation.

3. Restoration

   a. Nutrient inactivation.
   b. Selective discharge.
   c. Macrophyte harvesting.
   d. Chemical controls (algicides).

Group VI contains lakes with intermediate areas and mean depths, showing moderate to advanced eutrophication. In general, water quality problems are not severe enough to warrant drastic restoration techniques. In many cases, however, selected restoration procedures, such as macrophyte harvesting, chemical controls, and nutrient deactivation may be applicable. The main management priority, which will improve water quality most effectively on both a short and long term basis, is the limitation of nutrient inputs.

Group VII

1. Wastewater treatment

    a. Treatment plants for communities in the watershed. Phosphorus removal required for many of these plants.
    b. Septic tank maintenance programs.

2. Land use practice and watershed management

    a. Shoreland corridors for agricultural areas adjacent to the lake and tributary streams.
    b. Protection of watershed wetland areas.
    c. Erosion control.
    d. Zoning and development regulation.

3. Restoration

    a. Macrophyte harvesting.
    b. Chemical controls.
    c. Sediment consolidation by drawdown.
    d. Dilution/flushing.

Group VII lakes are similar to those in Group VI, but are shallower. Since water quality problems are usually not severe enough to warrant drastic restoration procedures, the primary management priority is to limit nutrient inputs. In some cases, selected restoration techniques may be advisable. A wider variety of techniques could be used for the restoration of these lakes than for those in Group VI because of their shallower depths.

Several advantages of this management plan are evident. Since morphometry plays a critical role in determining the trophic nature of a lake, the use of area and mean depth in determining management groups provides a theoretically valid framework for the plan. For example, shallow lakes which continual mixing can be expected to exhibit different characteristics than deep stratified lakes, where the sediments are exposed to mixing only at spring and fall turnover. Lakes with large surface areas will be more affected by wind-generated mixing, and usually have larger drainage basins than small lakes. In addition to theoretical considerations, use of area and mean depth in the management plan has practical importance in selecting lake protection and restoration procedures. For example, many restoration techniques (e.g., dredging, nutrient inactivation, etc.) are not suitable management policies for lakes with large surface areas because of high costs. Small lakes with small watersheds are more easily managed than large lakes. Depth is an important factor for management decisions, since some restoration techniques such as selective discharge and nutrient inactivation are only effective in well-stratified lakes.

Several advantages are also realized by the incorporation of a measure of lake trophic state in the management plan. All lake problems are influenced to a greater or lesser degree by lake trophic state. Therefore, management policies should be based on a knowledge of the trophic condition of the lake. Furthermore, the selection of specific lake protection and restoration techniques is dependent on the trophic characteristics of the lake. For example, lakes with severe algal and macrophyte problems and large internal nutrient concentrations, may require drastic restoration procedures, such as dredging or bottom sealing. On the other hand, lakes with less severe water quality problems could be more easily and effectively managed through nutrient input abatement programs.

Today virtually all lake problems in the state are caused or related to cultural eutrophication. Therefore, solutions to lake problems must ultimately address the causes of cultural eutrophication. Since increased nutrient input forms the basis of cultural eutrophication, nutrient abatement programs must be instituted to prevent further degradation of water quality. In the proposed management plan, nutrient abatement procedures are recognized as a priority for all lake groupings.

Indiana has developed several programs which work toward nutrient abatement in lakes and reservoirs. One of the most important of these is the enactment of the Phosphate Detergent Law (IC 13-1-5.5 as amended) which became fully effective in 1973. This law limits the amount of phosphorus in laundry detergents to that amount incidental to the manufacturing of these detergents (not to exceed 0.5%). Additionally, Regulation 330 IAC 5, governing the issuance of NPDES permits, requires phosphorus removal for all discharges containing ten pounds or more of total phosphorus if the discharge is located in the Lake Michigan or Lake Erie basins, on a lake or reservoir, or on a tributary within 40 miles upstream of the lake or reservoir. Phosphorus removal may also be required irrespective of the amount of phosphorus in the discharge if it is determined that phosphorus reduction is needed to protect water uses or to meet water quality standards.

Indiana has also developed a proposed Lake Discharge Policy requiring quite stringent limits for both continuous and controlled discharges to lakes and reservoirs or to tributaries of lakes or reservoirs within two miles upstream of these waterbodies. These proposed guidelines prohibit the release of controlled discharges directly to lakes or reservoirs or to tributaries within one-half mile upstream of such waterbodies. If the controlled discharge is located from one-half to two miles upstream of a lake or reservoir, no releases can occur during the summer months (May through September) or when receiving stream dilution would be less than 5:1. Several additional factors are to be reviewed on a case-by-case basis for these controlled discharges.

Indiana's Confined Feeding Control Law (IC 1971, 13-1-5.7) and the Land Application Regulation (330 IAC 3.3) contain provisions governing the land application of sludges and animal wastes. These requirements are designed to prevent or reduce runoff of these materials to rivers, streams, lakes and reservoirs and thus reduce input of nutrients and other materials from nonpoint sources to Indiana's waterbodies.

Indiana recognizes the important role that wetlands have in maintaining the water quality of lakes and reservoirs. These wetlands act as nutrient and sediment traps which "filter out" these materials before they reach the lake or reservoir and cause problems. Substantial effort is made to protect wetlands, especially those contiguous to lakes and reservoirs or their tributaries, through the Section 404 environmental review and Section 401 certification process and the early environmental coordination of proposed construction processes not requiring Section 401 certification.

Additionally, as a result of a soil erosion study by the Governor's Soil Resources Study Commission, the 1986 legislature has established a new Division of Soil Conservation in the Indiana Department of Natural Resources and a State Conservation Board to serve as a policy-making body for the Division. Erosion control measures instituted by these bodies will include both agricultural and nonagricultural land and will eventually be part of a regulatory program. It is anticipated that a representative from the Department of Environmental Management will be a part of this new board. This representative would work to ensure that soil conservation measures needed to protect lakes and reservoirs are incorporated into the programs to be implemented.

At the local level, the state works to encourage the enactment of zoning regulations and ordinances that would restrict undesirable activities on or near lakes whenever this opportunity presents itself. However, as far as the state can determine, there is no way to force such action on the part of local officials.

Part V. Recommendations for Future Lake Research and Restoration

The plan outlined in Part IV of this report provides a broad framework for management decisions for the lakes of Indiana. Since it is not feasible for the state to protect and restore the water quality of all lakes in the immediate future, the DEM must establish policies and guidelines for the allocation of their limited funds. These policies and guidelines will be used to establish a priority ranking of watershed improvement plans and lake improvement projects. Priority ranking for an individual lake is based upon the following four considerations:

1. Cost-effectiveness

The cost-effectiveness of a project involves the selection of a specific management strategy or restoration technique or combination of techniques (depending on the present status of the lake) and an assessment of the cost in relation to the effectiveness. Effectiveness of a particular technique is judged by the predicted improvement in water quality, both on a short and long term basis. Selection of appropriate techniques must follow the guidelines of the broad lake management plan and must be based on the identification of lake degradation causes. To identify these causes, studies must be conducted to assess the relative contributions of various nutrient sources to the lake. Such sources may include point sources (sewerage and industrial effluent discharges, tributary streams, etc.), non-point sources (agricultural and domestic runoff, septic fields, etc.) and internal nutrient pools (sediment loading, macrophytes, etc.).

Watershed protection may ultimately prove to be our most cost-effective measure in that protection of the state's presently unimpacted watersheds containing healthy lakes would prevent future problems and the possibility of costly solutions. The prudent management of these healthy watersheds (by state and local agencies) through regional planning and development regulation should be encouraged by the State of Indiana.

2. Types of lake usage

Lake usage is defined as the human activities which occur in relation to the lake. These include residential use (both permanent and seasonal), recreational use (fishing, swimming, boating, etc.), industrial and municipal use (water supplies), and local business use (resorts, boat liveries, marinas, bait and tackle shops, etc.). An evaluation should address not only the types of use, but also the relative importance of each type.

3. Amount of use

Amount of use involves an evaluation of the actual numbers of people engaged in the various types of lake usage and the amount of time people devote to these usages. Consideration should also be given to the geographic, economic, and sociological representation and implications of human use. The relative importance of a lake as a local resource will influence priority ranking decisions.

4. Availability of local support and funding.

In general the state will give high priority to watershed protection plans and lake improvement projects for which there is strong local support in the form of both community involvement and/or matching funds.

These four points collectively constitute the basis upon which the state can conduct cost-benefit analyses as a tool for priority ranking of lake improvement and watershed protection projects throughout the state. The future of Indiana's lakes rests upon the continued cooperation and effort of federal, state, and local governments as well as concerned citizens. The ISBH (DEM) has completed Phase I of a three-phase comprehensive lake program. This report marks the transition from the evaluation of statewide lake water quality conditions (Phase I) to the identification and solution of individual lake problems as well as the designation and protection of healthy watersheds threatened by poor or no management and development practices. Although much still remains to be done, the future now holds promise for the improvement of Indiana lakes.

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Appendix I. Morphometric and trophic characteristics of Indiana Lakes

The Eutrophication Index is derived from the parameters listed on pages 36 and 37.

Lake Name	Trophic Class	Size (Acres)	Maximum Depth (ft.)	Mean Depth (ft.)	Total Phosphorus (mg/l)	Secchi Disc (ft.)	Eutrophication Index	Lake Management Group
Adams Co.								
Rainbow	Two	45	16.0	6.0	0.07	1.5	41	VII C
Saddle	Two	24	10.0	10.0	0.04	2.0	41	VII C
Allen Co.								
Cedarville Res.	Three	245	20.0	4.0	0.12	1.5	61	IV A
Bartholomew Co.								
Grouse Ridge	Two	20	25.0	10.0	0.10	4.0	25	VII A
Brown Co.								
Bear Creek	One	7	27.0	10.0	0.03	5.0	7	V
Crooked Creek	One	13	27.0	10.0	0.03	5.0	10	V
Ogle	One	20	24.0	12.5	0.03	5.0	8	V
Strahl	One	6	23.0	9.0	0.05	5.0	10	V
Yellowwood	One	133	30.0	14.2	0.04	14.2	10	V
Carrol Co.								
Freeman	Two	1,547	44.0	16.8	0.19	3.5	38	III
Clark Co.								
Bowen	One	7	22.0	6.0	0.05	6.0	13	V
Deam	One	195	33.0	12.5	0.01	10.0	5	V

Franke	Two	9	18.0	7.8	0.05	4.0	35	V
Oak	One	3.5	13.0	8.0	0.03	8.0	8	V
Pine	Three	1.5	11.0	6.0	0.05	4.0	55	IV A
Schlamm	One	19	24.0	8.9	0.03	8.0	10	V
Clay Co.								
Brazil Waterworks Pond	Three	15	15.0	6.0	0.52	1.0	67	IV B
Crawford Co.								
Sulphur	Two	1	10.0	5.0	0.03	5.0	26	VII A
Daviess Co.								
Dogwood	One	1,300	40.0	18.0	0.03	11.5	16	III
Indian Rock	Two	100	20.0	10.0	0.06	10.5	37	VII A
Decatur Co.								
Greensburg State Fishing Area Lake (1975)	Three	23	14.0	6.0	0.23	2.5	60	IV A
Surface Only (1985)		--	--	--	0.17	8 in.	65	IV A
Dekalb Co.								
Cedar	Three	28	30.0	8.2	0.08	2.5	40	VII C
Lintz	Three	19	35.0	15.0	0.11	4.0	53	IV B
Story	Three	77	32.0	13.2	0.33	2.0	60	IV B
Delaware Co.								
Prairie Creek Reservoir	Two	1,216	30.0	15.0	0.05	5.5	36	III

Dubois Co.								
Ferdinand (Ferdinand State Forest)	Three	42	23.0	10.5	0.04	5.0	55	IV B
Ferdinand 1	One	16	17.0	10.0	0.03	--	20	VII A
Holland 1	Two	17	12.0	10.0	--	0.6	27	VII A
Holland 2	Two	20	14.0	10.0	--	7.0	25	VII A
Huntingburg City	Two	102	30.0	12.0	0.03	5.0	18	V
Elkhart Co.								
Fish	Three	34	30.0	10.0	0.11	6.5	35	VII A
Heaton	One	87	22.0	7.4	0.02	10.0	10	V
Hunter	One	99	29.0	11.3	0.06	6.5	20	VII A
Indiana	One	122	29.0	27.9	0.02	9.5	11	II A
Simonton	One	282	40.0	5.5	0.02	5.0	6	II A
Yellow Creek	Three	16	20.0	4.0	0.34	1.3	58	IV A
Franklin Co.								
Brookville Res. 1979	(Dam)	5,260	120.0	25.0	0.02	4.0	23	I
Brookville Res. 1985	(Dam)	--	--	--	0.03	46 in.	21	
Fulton Co.								
Anderson	Two	14	25.0	5.0	0.04	5.0	31	VII A
Barr	Two	5	48.0	12.0	0.06	5.0	35	VI A
Bruce	Three	245	18.0	14.0	0.12	2.5	61	IV B
Fletcher	Two	45	60.0	15.0	0.14	6.8	45	VII B
King 1976 Estimate (Low)	Two	18	35.0	10.0	--	5.0	35	IV B
King 1985	Three	--	--	--	0.046	2.0	56	VII A
Lake 16	Two	27	30.0	8.1	0.10	6.0	32	VII A
Manitou	Two	~~713~~ 1156	35.0	8.8	0.11	3.5	48	III
Millark Pond	Four	15	6.0	5.0	0.06	5.0	65	IV A
Mt. Zion Mill Pond	Four	28	6.0	5.0	0.05	5.0	65	IV A
Nyona (S. Bas.)	Three	104	32.0	12.9	0.12	5.0	54	IV B

Rock	Three	56	16.0	11.0	0.07	2.5	61	IV B
South Mud	Three	94	20.0	10.9	0.25	1.0	66	IV B
Town	Three	22	16.0	9.6	0.21	4.0	64	IV B
Upper Summit	Two	6	40.0	15.0	0.04	6.0	42	VII B
Zink	Two	19	40.0	12.0	0.04	6.0	28	VII A
<u>Hamilton Co.</u>								
Morse Res. 1975	Two	1,375	40.0	15.4	0.10	4.5	31	III
Morse Res. 1985	Two	1,375	40.0	15.4	0.036	4.0	22	
<u>Howard Co.</u>								
Kokomo Res. 2	Three	484	22.0	7.0	0.18	1.5	66	IV C
<u>Huntington Co.</u>								
Salamonie Res. 1975	Two	2,800	60.0	16.6	0.04	2.5	21	I
Salamonie Res. 1985	Two	2,800	60.0	16.6	0.03	4.3	18	
Huntington Res 1975	Two	900	36.0	17.0	0.06	3.0	25	III
<u>Jackson Co.</u>								
Cypress	Two	200	20.0	5.0	0.10	2.5	49	V
Starve Hollow	Two	145	17.0	6.8	0.03	9.0	(Atypical) 58	VII A
<u>Jennings Co.</u>								
Brush Creek Res.	Two	167	32.0	10.0	0.07	4.0	55	VII B
<u>Knox Co.</u>								
Brodie	Four	19	12.0	4.0	0.36	1.0	64	V
Halfmoon Bed Pond	Four	38	8.0	5.0	0.19	1.0	55	V
Long Ponds	Four	38	8.0	4.0	0.29	1.0	58	V
Mariah Pond	Four	50	10.0	5.0	0.31	1.3	62	V

Oaktown Bed	Four	15	10.0	3.0	0.13	1.5	48	V
Sandborn Old Bed	Four	30	8.0	6.0	0.35	1.0	54	V
White Oak	Three	30	15.0	5.0	0.12	1.5	55	IV A
Kosciusko Co.								
Barrel	Four	7	50.0	35.0	0.08	5.0	46	V
Beaver Dam	Three	146	61.0	22.5	0.85	4.0	55	IV D
Big Barbee	Two	304	49.0	18.6	0.05	5.0	38	VI A
Big Chapman (W. Bas.)	One	581 (total)	35.0	10.5	0.01	10.0	18	VII A
Big Chapman (N. Bas.)	--	--	30.0	10.5	0.01	10.0	19	VII A
Boner	Two	40	60.0	9.2	0.35	7.5	43	VII C
Caldwell	Two	45	42.0	17.8	0.12	6.0	46	VII B
Carr	Three	79	35.0	17.0	0.14	3.5	50	VII B
Center	Two	120	42.0	17.2	0.04	4.5	31	VII B
Crystal	One	76	41.0	12.2	0.03	6.0	10	V
Daniels	Four	8	25.0	25.0	0.03	6.0	18	V
Dewart (NW. Bas.)	Two	551 (total)	70.0	16.3	0.03	5.5	36	VII B
Dewart (SE. Bas.)	Two	--	--	--	0.03	6.0	36	VII B
Dewart (SW. Bas.)	Two	--	--	--	0.03/0.03	6.0	36	VII B
Flatbelly	Three	326	49.0	13.3	0.02	8.0	54	IV B
Goose	One	27	61.0	20.0	0.03	9.0	15	VI A
Heron	Two	22	30.0	12.0	0.03	5.0	22	VII A
Hill	Two	66	35.0	19.4	0.12	12.0	31	VI A
Hoffman	Two	180	34.0	17.6	0.02	8.5	23	VI A
Irish	Two	182	35.0	12.8	0.05	7.0	45	VII C
James	Two	282	63.0	26.9	0.04	6.5	39	VI B
Kuhn	Two	137	27.0	9.4	0.01	9.8	15	V
Little Barbee	Three	74	26.0	13.0	0.08	5.0	56	VII B
Little Chapman	Two	177	30.0	11.2	0.03	7.0	25	VII A
Little Pike	Two	25	30.0	5.6	0.09	2.5	31	VII A
Loon	Three	40	30.0	16.8	0.05	2.5	52	IV B
McClures	Two	32	30.0	12.8	0.05	2.5	51	VII B
Muskelonge	Two	32	21.0	9.4	0.14	1.8	40	VII C
North Little	Three	12	26.0	10.0	0.12	2.5	52	VI B
Oswego	Two	41	36.0	20.0	0.04	5.5	33	VI A

Palestine (East Basin)	Three	232 (total)	25.0	8.0	0.91	0.5	56	IV B
Palestine (West Basin)	Three	--	--	--	0.54	0.5	54	IV B
Pike 1975	Two	203	35.0	13.9	0.09	3.0	37	IV B
Pike 1985	Two	--	--	--	0.12	3.0	45	IV B
Price	Three	12	40.0	20.0	0.10	8.0	50	V
Ridinger	Two	136	42.0	21.0	0.05	3.5	58	VII B
Sawmill	Two	36	26.0	10.3	0.01	5.5	33	VII A
Sechrist	One	105	26.0	23.7	0.02	9.0	24	VI A
Shock	Two	37	59.0	32.7	0.23	9.0	28	II C
Shoe	Two	40	60.0	40.0	0.04	8.5	14	II C
Silver	Three	102	33.0	14.9	0.34/0.19	2.8/2.5	51	IV B
Spear	Two	18	34.0	25.0	0.19	9.0	36	VI A
Stanton	Two	32	30.0	15.0	0.01	12.0	20	VI A
Syracuse	One	414	35.0	12.9	0.01	13.0	4	V
Tippecanoe	One	768	123.0	37.0	0.05/0.04	7.0/6.5	12	II B
Wabee	Three	187	51.0	25.4	0.07	4.8	60	IV D
Wawasee (Mid-E. Bas.)	One	3,060 (total)	--	--	0.03	8.0	16	I
Wawasee (S. Bas.)	One	--	77.0	22.0	0.04	7.5	15	I
Wawasee (SE. Bas.)	One	--	--	--	0.03	7.5	18	I
Webster	Two	774	45.0	7.0	0.06	3.0	37	VII A
Winona (Central Bas.)	Three	562	80.0	29.7	0.13	3.5	56	IV D
Yellow Creek	Three	151	60.0	31.3	0.09	2.5	67	IV D
LaGrange Co.								
Adams	One	308	91.0	25.0 (Atypical)	0.14	10.0	28	VI A
Appleman	Two	52	26.0	11.3	0.035	6.0	30	VII A
Big Long	Two	388	82.0	40.0	0.06	11.0	33	II C
Blackman	Two	67	60.0	18.1	0.05	9.0	20	VI A
Brokesha	One	36	40.0	10.0	0.03	8.0	11	V
Cedar	One	120	30.0	8.5	0.03	10.0	9	V
Cline	Four	20	31.0	17.5	0.03	6.0	9	V
Cotton	Three	31	25.0	30.0	0.11	3.5	66	IV D
Dallas	Two	283	96.0	35.2	0.33/0.05	9.0/6.5	28	II C
Emma	Two	42	34.0	16.7	0.04	4.0	44	VII B

Eve	Two	31	42.0	21.6	0.03	8.0	18	VI A
Fish	Two	100	78.0	40.5	0.04	6.0/5.0	39	II C
Green (Rawles)	Four	62	10.0	5.0	Ill. Res.	5.0	51	V
Hackenberg	Two	42	38.0	12.1	0.07	6.5	29	VII A
Hayward	Two	6	20.0	15.0	Ill. Res.	6.0	43	V
Lake of the Woods	One	136	84.0	40.2	0.03	9.5	18	II C
Little Turkey	Two	135	30.0	11.5	0.16	7.0	36	VII A
Martin	One	26	56.0	34.2	0.33/0.04	10.5/6.0/5.5	35	II C
Meteer	One	18	18.0	8.3	0.03	12.5	17	V
Meesick	Two	68	55.0/54.0	21.3	0.10/ 0.13	8.5/6.5	34/26	VI A
Mongo Res.	Three	24	15.0	15.0	0.08	2.5	54	V
Nasby Mill Pond	Two	35	15.0	10.0	0.05	2.5	41	V
Nauvoo	Three	38	40.0	25.0	0.05	3.0	50	VI A
North Twin	One	135	30.0	15.7	0.03	5.8	13	V
Olin	One	103	82.0	38.0	0.01/0.03	9.0/7.0	10	II B
Oliver	One	362	91.0	40.0	0.01/ 0.03	12.0/10.0	10	II B
Pigeon (North)	Two	61	35.0	19.0	0.065	8.0	27	VII B
Pretty	One	184	84.0	25.7	0.08	10.0	25	VI A
Rainbow	Two	16	40.0	15.6	0.03	2.6	31	VII B
Royer	Two	69	59.0/56.0	23.6	0.16	8.0/6.2	26	VI A
Shipshewana	Three	202	14.0	6.7	0.045	3.0	51	IV A
South Twin	One	116	52.0	31.0	Ill. Res.	8.0	8	II A
Spectacle Pond	Three	6	20.0	7.5	Ill. Res.	8.0	52	V
Star Mill Pond	Four	38	10.0	10.0	0.03	4.0	43	V
Still	One	30	58.0	20.7	0.03	8.0	19	VI A
Stone	One	116	58.0	14.7	0.03	10.0	2	V
Wall	One	141	34.0	11.0	0.03	9.5	13	V
Weir	Four/One	6	70.0	30.0	0.03	9.0	10	V
Westler	Two	88	38.0	20.1	0.03	7.0/4.0	25	VI A
Witmer	Two	204	54.0	34.5	0.09	6.5	27	II C
Lake Co.								
Cedar	Three	781	16.0	8.6	0.20/0.52/0.37/ 0.32/0.35	1.2/0.8	70	IV C
Dalecarlia	Three	193	--	6.0	0.30	1.0	51	IV A
George (North Basin)	Three	78 (total)	12.0	3.0	Ill. Res.	3.5	55	IV A

George (South Basin)			12.0	3.0	Ill. Res.	2.0	55	IV A
George (Hobart)	Three	282	14.0	5.0	0.19	1.0	55	IV A
Wolf (Ill. Basin)	Three	385 (total)	8.0	5.0	0.04	3.0	59	IV A
Wolf (Main Ind. Basin)	--	--	15.0	5.0	0.09	3.0	58	IV A
<u>LaPorte Co.</u>								
Clear	Two	106	12.0	7.2	0.02	7.0	30	VII A
Crane	Three	58	12.0	3.0	0.02	3.0	50	VII C
Fishtrap	One	102	37.0	10.0	0.03	5.0	18	V
Hog	One	59	52.0	11.7	0.02	13.0	21	VII A
Horseshoe	Three	35	10.0	3.0	0.09	5.0	60	V
Hudson	Two	432	42.0	11.7	0.02	5.5	23	VII A
Lily	Four	16	22.0	8.0	0.11	5.0	55	V
Lower Fish	One	134	16.0	6.5	0.02	6.0	8	V
Pine	One	282	71.0	13.0	0.03	10.0	22	VII A
Saugany (Atypical)	One	74	66.0	29.6	0.01	31.8	(Atypical) 1	II A
Stone	One	125	36.0	19.9	0.02	13.5	6	V
Swede	Two	33	15.0	8.0	0.04	4.5	32	VII A
Upper Fish	Two	139	24.0	7.5	0.03	7.5	22	VII A
<u>Marion Co.</u>								
Eagle Creek Res. 1975	Two	1,500	35.0	12.5	0.19/0.10/0.06	4.5/4.0/2.0	42/44/34	III
Eagle Creek Res. 1985	Two	--	--	--	0.45	3.0	35	--
Geist Res. 1973	Two	1,800	22.0	12.0	0.14/0.06	2.5	37	III
Geist Res. 1985	Two	--	--	--	0.12	3.0	4.2	--

Marshall Co.								
Cook	Two	93	64.0	17.7	0.18	9.0	40	VII B
Dixon	Two	33	48.0	14.5	0.26	7.0	30	VII B
Eddy	Two	16	49.0	25.0	0.09	5.0	42	VI A
Flat	Two	26	24.0	8.1	0.16	6.0	35	VII A
Gilbert	Three	37	41.0	13.2	0.43	1.0	75	IV B
Holem	One	30	74.0	9.8	0.03	8.5	23	VII A
Hawks (Lost)	Three	40	9.0	4.0	0.10	5.0	65	IV B
Koontz	Two	346	31.0	9.2	0.05	3.5	42	VII C
Kreighbaum	Two	20	28.0	20.0	0.07	11.0	32	VII A
Lake of the Woods	Two	416	48.0	16.4	0.09	3.0	42	VII B
Lawrence	One	69	63.0	22.9	0.02	13.0	13	II A
Maxinkuckee	One	1,864	88.0	24.5	0.01/ 0.03	7.5	18	III
Meyers	One	96	59.0	20.8	0.06	11.8	21	VI A
Mill Pond	Four	136	36.0	6.1	0.08	5.0	58	IV A
Pretty	One	97	40.0	22.1	0.04	14.5	28	IV A
Thomas	Three	16	58.0	27.0	0.06	4.5	51	V D
Martin Co.								
Boggs Creek	Two	600	30.0	12.5	0.04	3.0	45	VII B
Trinity Springs	Three	10	7.0	2.0	0.18	2.0	60	IV A
Miami Co.								
Mississinewa Res. Dam 1975	One	3,180	45.0	17.5	0.02/ 0.03	6.5/5.0/4.7/3.5 3.0/2.0/1.5/1.2	20/16	I
Mississinewa Res. Dam 1985	One	--	--	--	0.081	5.0	24	I
Monroe Co.								
Cherry	One	4	30.0	12.0	0.01	8.0	15	V
Bryants Creek Lake	One	9	23.0	10.0	0.02	6.0	15	V
Griffey Res.	Three	130	30.0	10.0	0.30	7.5	40	VII C
Lemon	Three	1,650	28.0	10.0	0.50/0.04	4.0/3.0	42/37	III
Monroe Res.								

Dam 1976	One	10,750	38.0	15.0-20.0	0.03	12.0	25	I
Monroe Res. Dam 1985	--	--	--	--	0.03	7.0	3	
Monroe Res. (Causeway)	--	--	--	--	0.04	6.0	34	I
Monroe Res. (Moores C.)	--	--	--	--	0.04	8.0	25	I
Monroe Res. (N. Salt C.)	--	--	--	--	0.03	8.0	29	I
Monroe Res. (N. Salt Cr.) 1985	--	--	--	--	0.04	2.0	19	I
Monroe Res. (Paynetown) 1976	--	--	--	--	0.03	8.0	27	I
Monroe Res. (Paynetown) 1985	--	--	--	--	0.03	3.3	15	I
North Twin 1976	Three	10	8.0	4.0	3.80	3.0	70	IV A
North Twin 1985	Three	--	--	--	0.10	2.0	70	IV A
<u>Montgomery Co.</u>								
Waveland	Two	360	27.0	10.0	0.03	5.0	20	VII A
<u>Newton Co.</u>								
J. C. Murphy	Two	1,515	8.0	5.0	0.045	1.5	47	III
<u>Noble Co.</u>								
Bartley	Two	34	34.0	12.6	0.07	7.2	35	VII A
Baugher	Three	32	36.0	12.2	0.08	3.0	54	IV B
Bear	Two	136	59.0	22.3	0.22	4.5	46	VI B
Big	Two	228	70.0	24.7	0.17	3.0	38	VI B
Bixler	Two	120	43.0	17.4	0.09	8.0	38	VII B
Bowen	Two	30	36.0	15.0	0.04	7.0	41	VII B
Crane	Two	28	26.0	12.9	0.04	9.0	45	VII B
Cree	Two	58	26.0	15.7	0.07	5.3	39	VII B

Crooked	One	206	108.0	43.9	0.03	10.0/9.0	3	II B
Diamond	Two	105	81.0	14.0	0.03	6.0	21	VII A
Dock	Two	16	40.0	16.6	0.05	7.0	38	VII B
Duely	Four	21	19.0	8.6	0.09	5.0	42	V
Engle	Two	48	29.0	14.0	0.03	8.0	26	VII A
Gilbert	Two	28	36.0	17.5	0.03	7.0	28	VII B
Gordy	Two	31	35.0	21.9	0.11	7.5	43	VII B
Hall	One	10	35.0	18.0	0.03	8.0	16	V
Harper	Three	11	25.0	14.5	0.03	5.1	60	VII B
Henderson	Three	22	35.0	15.0	1.00	1.0	73	IV B
High	Two	123	25.0	10.1	0.07	4.0	53	VII B
Hindman	Four	13	20.0	10.8	0.42	7.0	52	V
Horseshoe	Two	18	28.0	13.9	0.40	6.5	40	VII C
Indian (Village)	Four	12	22.0	13.3	0.06	5.1	59	V
Knapp	Two	88	59.0	25.0	0.23	11.0	43	VII A
Latta	Two	42	38.0	21.4	0.05	5.0	36	VI A
Little Long	Two	71	32.0	24.6	0.04	5.0	32	VI A
Long (Chain of Lakes)	Two	40	32.0	15.8	0.04	7.0	33	VII B
Millers	Two	28	34.0	14.6	0.05	8.0	35	VII B
Moss	Four	9	19.0	8.9	0.24	8.0	51	V
Muncie	Two	47	37.0	12.3	0.09	3.0	46	VII C
Norman	Three	14	46.0	20.0	0.18	11.0	39	VI A
Pleasant	Two	20	67.0	27.0/22.5	0.21	8.0	29	VI A
Port Mitchell	Two	15	31.0	12.0	0.19	8.0	30	VII A
Rider	Four	5	15.0	6.0	0.07	7.5	55	V
Rivir (Chain of Lakes)	Three	24	32.0	15.8	0.07	6.0	38	VII B
Round	Two	99	66.0	21.6	0.05	5.0	24	VI A
Sacarider	Two	33	60.0	22.4	0.25	9.0	35	VI A
Sand (Chain of Lakes)	Two	47	51.0	27.0	0.05	9.0	23	VI A
Shockopee	Two	21	26.0	13.3	0.04	5.0	30	VII A
Skinner	Three	125	32.0	14.0	0.04	4.0	45	VII C
Smalley	Two	69	49.0	22.0	0.05	7.0	34	VI A
Sparta	Two	31	10.0	5.5	0.04	6.0	40	VII C
Stienbarger	Two	73	39.0	21.8	0.09	6.0	39	VI A
Sylvan	Three	575	36.0	14.0	0.09	5.0	62	IV C
Tamarack	Two	50	37.0	17.6	0.23	5.2	42	VII A

Upper Long	Two	86	54.0	22.1	0.17	7.0	32	VI A
Waldron	Two	216	45.0	14.4	0.24	3.2	43	VII C
Wible	Three	49	27.0	13.3	0.08	4.0	55	IV B
Wolf	Four	25	14.0	8.0	0.33	5.0	43	IV B
<u>Orange Co.</u>								
Springs Valley	One	141	26.0	8.0	0.03	6.0	20	VII A
<u>Parke Co.</u>								
Raccoon (Mansfield)	Two	2,060	60.0	15.0	0.07	4.0	21	III
Rockville	Two	100	30.0	15.0	0.31	5.0	47	VII B
<u>Perry Co.</u>								
Celina	One	164	38.0	15.0/20.0	0.03	8.0	10	V
Fenn Haven	Three	20	10.0	4.0	0.03	2.0	55	IV A
Oriole	Two	1	8.0	5.0	0.08	4.0	39	VII C
Indian	One	149	25.0	15.0	0.03	9.0	20	VI A
Saddle	Two	41	20.0	15.0	0.03	6.0	36	VI A
Tipsaw	One	131	15.0	15.0	0.03	8.0	19	VI A
<u>Pike Co.</u>								
West Lake	Two	15	25.0	10.0	0.03	7.0	7	V
Prides Creek	Two	90	20.0	10.0	0.80	4.0	33	VII A
<u>Porter Co.</u>								
Billington	Two	11	10.0	10.0	0.13	5.0	35	V
Canada	Two	10	36.0	10.0	0.08	5.0	39	V
Clear	One	17	30.0	15.0	0.03	8.0	22	VI A
Deep	Two	7	7.0	10.0	0.03	5.0	28	
Eliza	Three	45	35.0	15.0	0.08	3.8	42	VII B
Flint	One	86	67.0	20.0	0.03	18.0	25	VI A
Long	Two	65	27.0	8.0	0.04	4.0	33	VII A
Loomis	Three	62	30.0	15.0	0.04	4.0	56	IV B

Mink	Three	35	24.0	10.0	0.06	2.0	50	VII C
Morgan	Two	12	15.0	15.0	0.04	5.0	28	VII C
Moss	Two	9	20.0	9.0	0.03	7.0	24	VII A
Spectacle	Two	62	30.0	8.7	0.09	5.0	40	VII C
Wahob	Two	21	48.0	35.0	0.11	7.0	31	II C
Posey Co.								
Hovey	Four	242	51.0	4.0	0.06	0.7/1.5	60	V
Putnam Co.								
Cataract (Lieber)	Three	1,400	36.0	20.0	0.08	2.5	50	III
Ripley Co.								
Bischoff	Two	200	27.0	15.0	0.12	2.5	63	VII B
Feller	Three	6	8.0	4.0	0.28	3.0	64	IV A
Hahn	Two	8	12.0	6.0	0.04	5.0	46	VII A
Liberty Park	Two	11	18.0	7.0	0.06	5.0	26	VI A
Mollenkramer	Three	93	10.0	5.0	0.10	4.0	59	V
Oser	Two	12	18.0	9.0	0.16	5.0	34	VII A
Versailles 1975	Three	230	20.0	5.0	0.11	1.5	52	VII A
Versailles 1985	Two	--	--	--	0.13	2.0	30	--
St. Joseph Co.								
Bass	One	88	37.0	10.0	0.01	10.7	17	V
Chamberlain	Four	51	27.0	3.5	0.03	5.0	50	IV A
Czmanda	Four	90	9.0	5.0	0.06	5.0	50	IV A
Mud	Four	197	8.0	2.0	--	5.0	50	IV A
Pleasant	Two	29	39.0	18.0	0.11	3.4	29	VII B
Potato Creek Res.	Two	300	--	15.0	0.03	6.5	25	VII A
Quarry	Two	43	64.0	15.0	0.04	6.0	30	VI A
Riddles	Two	77	20.0	8.3	0.02	4.0	30	VII A
Sously	Two	40	19.0	4.0	0.04	4.0	50	IV A
South Clear	Three	51	15.0	2.0	0.08	5.0	50	IV A

Scott Co.								
Hardy	Two	705	40.0	12.0	0.02	5.0	19	VII A
Scottsburg Res.	Three	83	16.0	4.0	0.11	1.0	63	IV A
Spencer Co.								
Lincoln	Two	58	24.0	12.0	0.03	4.5	29	VII A
Starke Co.								
Bass	Two	1,400	30.0	10.0	0.70/0.02	2.5	39/36	III
Eagle	Two	24	12.0	6.7	0.04	5.0	40	VII C
Hartz	One	28	40.0	13.2	0.05	9.0	23	VII A
Langenbaum	Three	48	19.0	5.4	0.03	7.0	41	VII C
Steuben Co.								
Ball	One	87	66.0	40.5	0.04	6.0	34	II C
Barton	Two	94	44.0	14.3	0.12	8.0	32	VII B
Bass	Two	61	20.0	7.4	0.06	11.0	34/31	VII A
Beaver Dam	Two	11	26.0	15.0	Illogical Results	10.0	27	V
Bell	Two	38	24.0	13.4	0.05	10.0	24	VII A
Big Bower	Three	25	22.0	11.2	0.16/0.09	3.0/3.0	66	IV B
Big Center	Three	46	19.0	8.5	0.33	1.5	71	IV B
Big Otter	Two	69	38.0	25.8	0.14	8.0	52	IV D
Big Turkey	Two	450	65.0	16.2	0.07	5.0	44	VII B
Black	Two	18	35.0	15.0	0.03	5.0	36	VII B
Booth	Four	10	40.0	14.0	0.04	5.0	55	IV B
Buck	Four	20	57.0	15.0	Illogical Results	5.0	30	VI A
Charles	Three	150	10.0	5.0	0.14	1.3	75	IV C
Cheeseboro	Two	27	16.0	10.0	0.05	5.0	40	VII C
Clear	One	800	107.0	31.2	0.17	7.5	25	II B
Crockett	Four	5	15.0	15.0	0.05	5.0	49	VII B
Crooked (Middle Bas.)	One	828	77.0	12.8	0.05	8.0	23	VII A
Deep	Four	12	28.0	10.0	0.06	5.0	51	V
Failing	One	23	35.0	8.0	0.01	15.0	20	V
Fish	Three	59	34.0	12.7	0.14	4.5	54	IV B

Fox	Two	142	55.0	22.2	0.07	9.0	27	IV A
Gage	One	332	70.0	30.6	0.03	12.0/8.0	8	II B
George		488	71.0	25.0	0.03	6.0	9	II B
Golden (Middle Bas.)	Three	119 (total)	15.0	15.2	0.06	3.0	66	IV B
Golden (NW. Bas.)	Three	--	15.0	15.2	0.12	3.5	71	IV B
Golden (SE. Bas.)	Three		31.0	15.2	0.06	3.0	66	IV B
Gooseneck	One	25	28.0	20.0	0.03	7.0	15	VI A
Grass	Four	20	25.0	10.0	0.03	5.0	24	V
Gravel	One	12	89.0	10.0	0.05	5.0	19	VII A
Gravel Pit	One	28	29.0	15.0	0.03	9.0	12	VI A
Green	One	24	27.0	10.0	0.02	9.5	15	VII A
Hamilton	Two	802	70.0	20.7	0.03	5.5	31	VI C
Handy	Four	16	41.0	18.1	0.04	10.0	35	V
Henry	Four	20	25.0	15.0	0.32	5.0	38	VII B
Hogback (NE. Bas.)	Three	146	26.0	10.1	0.28/0.04	4.6/2.5/4.0	59/57	IV B
Hogback (SW. Bas.)	Three	--	--	10.1	0.07/0.04	4.0	60	IV B
Howard	Four	27	12.0	4.8	Illogical Result	5.0	64	IV A
James (Upper Bas.)	One	1,034 (total)			0.03	12.0	16	II B
James (Middle Bas.)	One	--	86.0	32.5	0.03	12.0	22	II B
James (Lower Bas.)	One	--	--	--	0.03	12.0	17	II B
Jimmerson	One	346	56.0	36.0	0.04	13.0	22	II B
Johnson	Four	17	39.0	15.0	0.045	5.0	30	VI A
Lake Anne (Unique)	One	17	31.0	16.5	0.10	9.0	38	VI A
Lake Pleasant	Two	424	52.0	40.0	0.12	8.0	40	II C
Little Otter	Three	34	37.0	21.8	0.28	5.5	58	IV D
Lime	Four	30	29.0	11.0	0.03	10.0	10	V
Lime-Kiln	Two	25	22.0	10.0	0.04	5.0	42	VII C
Long A (Near (Pleasant)	Three	92	33.0	16.7	0.40/0.12	2.5	75/53	IV B
Long B	Two	154	36.0	11.9	0.03	7.3	24	VII A
Loon	Four	138	18.0	4.6	0.05	5.0	53	V

Marsh	Three	56	38.0/35.0	20.0	0.60/0.50/0.39	6.0/5.5/4.5	67/65/64	IV B
McClish	One	35	57.0	34.6	0.03	9.0	18	II C
Meserve	One	16	25.0	14.0	0.03	10.0	22	VII A
Middle Center	Three	15	20.0	5.0	0.50	5.0	62	IV A
Mirror	Four	9	60.0	13.3	0.03	10.0	25/12	VII A
Mud B	Four	16	40.0	18.0	0.05	5.0	59	VII B
Mud C	Four	20	32.0	6.0	0.25	5.0	48	VII C
Perch	Four	12	36.0	18.0	0.04	5.0	30	VII B
Pigeon (Big Bas.)	Three	61	38.0	15.2	0.18	5.0	57	IV B
Pigeon (Little Bas.)	Three	--	20.0	10.0	0.29	5.0	60	IV B
Pleasant	One	53	44.0	30.0	0.09	13.0	20	II A
Round A	Two	30	60.0	35.0	0.06	6.0	25	II C
Round B	Two	30	25.0	11.3	0.03	8.0	23	VII A
Round C	Two	12	30.0	10.0	0.05	7.0	38	VII A
Seven Sisters	Four	22	40.0	14.0	0.03	5.0	27	V
Shallow	Four	65	16.0	5.0	0.05	5.0	51	V
Silver	Two	238	38.0	10.7	0.03	9.5	28	VII A
Snow	One	421	84.0	30.0	0.03	10.5	20	II B
Snow (S. Bas.)	One	--	--	19.0	0.03	10.5	18	II B
Stayner	Four	5	10.0	7.0	0.03	7.0	51	V
Tamarack	Two	47	14.0	5.0	0.04	7.0	30	VII A
Walters	Four	53	29.0	10.4	0.03	8.0	26	V
Warner	Four	17	25.0	15.0	0.04	7.0	30	V
West Otter	Two	118	31.0	16.6	0.04	5.0	35	VII B
Sullivan Co.								
County Line Pit	Four	5	6.0	4.0	0.06	0.0	61	IV A
Jonay Res.	Three	11	18.0	6.0	0.07	6.0	32	VII C
Kelly Bayou	Four	40	6.0	3.0	0.19	1.5	64	IV A
Kickapoo	Two	30	40.0	23.0	0.02	6.0	21	VI A
Lake 29 (Acid)		--	--	--	0.10	--	--	
Lake Sullivan	Two	507	25.0	10.0	0.80	5.0	39	VII A
Merom Gravel Pits	One	55	50.0	6.0	0.03	10.0	5	V
Shakamak	Two	56	26.0	10.9	0.13	6.5	38	VII C

<u>Union Co.</u>								
Whitewater Lake	Two	199	46.0	15.0	0.06	8.5	29	VII B
<u>Vigo Co.</u>								
Fowler Park	Two	50	40.0	15.0	0.14	10.0	50	VII B
Greenfield Bayou	Four	61	12.0	5.0	0.11	5.0	52	V
Green Valley	Two	50	--	--	0.04	5.0	36	VII A
Hartman	Two	21	18.0	12.0	0.05	5.0	37	VII A
Izaak Walton	Two	83	60.0	25.0	0.07	5.0	40	VI B
<u>Wabash Co.</u>								
Hominy Ridge	Three	11	20.0	8.0	0.32	2.5	59	IV A
Long (at Laketon)	Two	48	39.0	16.0	0.04	7.0	30	VII B
Lukens	Two	46	41.0	22.0	0.09	10.0	30	VI A
Round (at Laketon)	Two	48	25.0	11.2	0.03	2.0	43	VII B
Twin Lakes	Two	81	16.0	10.6	0.05	4.5	50	IV B
<u>Warrick Co.</u>								
Scales	Two	66	20.0	7.0	0.04	15.0	50	VII C
<u>Washington Co.</u>								
Elk Creek	Two	47	32.0	12.5	0.04	17.0	13	V
John Hay	Two		40.0	15.0	0.03	8.0	13	VI A
Salinda	Three	70	20.0	15.0	0.36/0.03	11.0/4.5	63/31	IV B
<u>Wayne Co.</u>								
Middle Fork Res.	One	277	30.0	15.0	0.03	8.0	18	V
<u>Wells Co.</u>								
Kunkel	Three	25	19.0	6.0	0.06	1.5	59	IV A
Moser	Three	26	12.0	6.0	0.19	3.0	55	IV A

White Co.								
Shaffer Dam	Two	1,291	30.0	10.2	0.12	5.0	23	III
Whitley Co.								
Blue	Two	239	49.0	21.0	0.15	10.5	35	VI A
Cedar (Tri-Lake)	One	131	75.0	30.0	0.04	21.0	8	II A
Dollar	Four	10	59.0	15.0	0.10	18.0	29	V
Goose	Three	84	69.0	25.9	0.04	3.5	61	IV D
Little Crooked	Two	15	50.0	20.0	0.04	9.0	32	VI A
Loon	Two	222	96.0	25.8	0.05	9.5	46	IV D
New	One	50	44.0	17.6	0.03	12.0	7	II A
Old	Two	32	42.0	19.4	0.15	9.5	48	VII B
Round (Tri-Lake)	Three	125	63.0	25.0	0.06	10.0	30	VI A
Scott	Two	18	22.0	5.0	0.05	5.0	23	VII A
Shriner (Tri-Lake)	One	111	61.0	45.0	0.05	16.0	19	II B
Troy-Cedar	Three	93	88.0	27.3	0.08	4.5	60	IV D

Appendix II. Grouping of Indiana Lakes by Cluster Analysis

ID#	Lake	Size (Acres)	Mean Depth	Index
Group I				
422.	Brookville Reservoir	5260.0	7.4	23
397.	Wawasee (South Basin)	3060.0	22.0	15
379.	Wawasee (Mid-E Basin)	3060.0	22.0	16
380.	Wawasee (SE Basin)	3060.0	22.0	18
197.	Mississinewa Res.	3180.0	17.5	20
198.	Mississinewa Res.	3180.0	17.5	20
199.	Mississinewa Res.	3180.0	17.5	20
202.	Mississinewa Res.	3180.0	17.5	20
201.	Mississinewa Res.	3180.0	17.5	20
200.	Mississinewa Res.	3180.0	17.5	20
205.	Mississinewa Res.	3180.0	17.5	20
204.	Mississinewa Res.	3180.0	17.5	20
203.	Mississinewa Res.	3180.0	17.5	20
219.	Mississinewa Res.	3180.0	17.5	20
218.	Mississinewa Res.	3180.0	17.5	20
196.	Mississinewa Res.	3180.0	17.5	16
	Salamonie Res.	2800.0	16.6	18
	Monroe Res.	10750.0	15.0-20.0	25
Group II Subgroup A				
55.	Beaver Dam	146.0	22.5	16
444.	New	50.0	17.6	7
209.	Stone	125.0	19.9	6
315.	George	488.0	25.0	9
178.	Saugany	74.0	29.6	1
151.	South Twin	116.0	31.0	8
447.	Cedar (Tri-Lake)	131.0	30.0	8
330.	Gage	327.0	30.6	8
314.	Gage	332.0	30.5	8
32.	Indiana	122.0	27.9	11
	Simonton	282.0	5.5	6
	Lawrence	69.0	22.9	13
	Pleasant	53.0	30.0	30
Group II Subgroup B				
103.	Tippecanoe	768.0	37.0	12
104.	Tippecanoe	768.0	37.0	12
339.	James (Upper Basin)	1034.0	32.5	16
341.	James (Lower Basin)	1034.0	32.5	17
340.	James (Middle Basin)	1034.0	32.5	22
308.	Clear	800.0	31.2	25
454.	Shriner	111.0	45.0	19
257.	Crooked	206.0	43.9	3
258.	Crooked	206.0	43.9	3

259.	Crooked	206.0	43.9	3
138.	Olin	103.0	38.0	10
139.	Olin	103.0	38.0	10
143.	Oliver	362.0	40.0	10
144.	Oliver	362.0	40.0	10
142.	Oliver	362.0	40.0	10
141.	Oliver	362.0	40.0	10
140.	Oliver	362.0	40.0	10
127.	Lake of the Woods	136.0	40.2	18
	Jimmerson	434.0	36.0	22
	Snow	421.0	30.0	20

Group II Subgroup C

95.	Shock	37.0	32.7	28
159.	Witmer	204.0	34.5	27
160.	Witmer	204.0	34.5	27
119.	Dallas	283.0	35.2	28
118.	Dallas	283.0	35.2	28
391.	McClish	35.0	34.6	18
129.	Martin	26.0	34.2	35
130.	Martin	26.0	34.2	35
456.	Martin	26.0	34.2	35
255.	Bowen	30.0	36.0	41
247.	Knapp	88.0	34.5	41
122.	Fish	100.0	40.5	39
123.	Fish	100.0	40.5	39
286.	Ball	87.0	40.5	34
112.	Big Long	388.0	40.0	33
	Shoe	40.0	40.0	14
	Wahob	19.0	35.0	31
	Lake Pleasant	424.0	40.0	40
	Round A	30.0	35.0	25

Group III

189.	Maxinkuckee	1864.0	24.5	18
190.	Maxinkucke	1864.0	24.5	18
18.	Dogwood	1300.0	18.0	16
446.	Shaffer Dam	1291.0	10.2	23
41.	Manitou	1156.0	8.8	48
240.	J. C. Murphy	1515.0	5.0	47
210.	Eagle Creek Res.	1500.0	12.5	34
212.	Eagle Creek Res.	1500.0	12.5	34
280.	Bass	1400.0	10.0	36
281.	Bass	1400.0	10.0	39
231.	Eagle Creek Res.	1500.0	12.5	42
211.	Eagle Creek Res.	1500.0	12.5	38
214.	Geist Res.	1800.0	12.0	35
68.	Morse Res.	1375.0	15.4	40
9.	Freeman	1547.0	16.8	38
	Prairie Creek Res.	1216.0	15.0	36
	Huntington Res.	900.0	36.0	25
	Lemon	1650.0	10.0	42

	Raccoon Res.	2060.0	15.0	21
	Cataract Res.	1400.0	20.0	50

Group IV Subgroup A

3.	Cedarville Res.	245.0	4.0	61
170.	Wolf (Main Ind. Basin)	385.0	5.0	58
206.	Wolf (Illinois Basin)	385.0	5.0	59
169.	George (Hobart)	282.0	5.0	55
191.	Mill Pond	136.0	6.1	58
440.	Kunkel	25.0	6.0	59
375.	Kelly Bayou	40.0	3.0	64
335.	Howard	27.0	4.8	64
43.	Mt. Zion Mill Pond	38.0	5.0	65
167.	George (N. Basin)	78.0	3.0	55
168.	George (S. Basin)	78.0	3.0	55
173.	Horseshoe	35.0	3.0	60
327.	Chamberlain	51.0	3.5	50
278.	Sously	40.0	4.0	50
279.	South Clear	51.0	2.0	50
275.	Mud 7101	197.0	2.0	50
441.	Moser	26.0	6.0	55
463.	White Oak	30.0	5.0	55
150.	Shipshewana	202.0	6.7	51
166.	Dalecarlia	193.0	6.0	51
274.	Czmanda	90.0	5.0	50
	Pine	1.5	6.0	55
	Yellow Creek	16.0	4.0	58
	Millark Pond	15.0	5.0	65
	Trinity Springs	10.0	2.0	60
	North Twin	10.0	4.0	70
	Fenn Haven	20.0	4.0	55
	Feller	6.0	4.0	64
	Scottsburg Res.	83.0	4.0	63
	Middle Center	15.0	5.0	62
	County Line Pit	5.0	4.0	61
	Hominy Ridge	11.0	8.0	59

Group IV Subgroup B

46.	South Mud	94.0	10.9	66
291.	Big Bower	25.0	11.2	66
292.	Big Center	46.0	8.5	71
293.	Golden (SE. Basin)	119.0	15.2	66
295.	Golden (Middle Basin)	119.0	15.2	66
438.	Salinda	70.0	15.0	63
294.	Golden (NW Basin)	119.0	15.2	71
346.	Long A (Near Pleasant)	92.0	16.7	74
183.	Gilbert (Marshall Co.)	37.0	13.2	75
350.	Marsh	56.0	20.0	57
24.	Ferdinand State Park	42.0	10.5	55
325.	Hogback (NE. Basin)	146.0	10.1	57
	Brazil Waterworks Pond	15.0	6.0	55
	Lintz	19.0	15.0	53

	Bruce	245.0	14.0	61
	King	18.0	10.0	56
	Town	22.0	9.6	64
	North Little	12.0	10.0	52
	Palestine	232.0	8.0	54-56
	Pike	203.0	13.0	45
	Wolf	25.0	8.0	43
	Henderson	22.0	15.0	73
	Booth	10.0	14.0	55
	Twin Lake	81.0	10.6	50
	Hawks (Lost)	40.0	4.0	65
334.	Hogback (NE. Basin)	146.0	10.1	57
51.	Brush Creek Res.	167.0	10.0	55
324.	Hogback (SW. Basin)	146.0	10.1	60
337.	Hogback (NE. Basin)	146.0	10.1	59
45.	Rock	56.0	11.0	61
436.	Scales	66.0	7.9	50
390.	Mink	35.0	10.0	50
71.	Flatbelly	326.0	13.3	54
61.	Carr	79.0	17.0	50
343.	Long A (Near Pleasant)	92.0	16.7	53
86.	Loon	40.0	16.8	52
98.	Silver	102.0	14.9	51
97.	Silver	102.0	14.9	51
44.	Nyona (S. Basin)	104.0	12.9	54
313.	Fish	59.0	12.7	54
242.	Baugher	32.0	12.2	54
321.	Wible	49.0	13.3	55
83.	Little Barbee	74.0	13.0	56
87.	McClures	32.0	12.8	51
70.	Diamond	79.0	16.2	60
420.	Loomis	62.0	15.0	56
356.	Pigeon	61.0	15.2	57
22.	Story	77.0	13.2	60

Group IV Subgroup C

306.	Charles	150.0	5.0	75
317.	Sylvan	575.0	14.0	62
161.	Cedar	781.0	8.6	70
162.	Cedar	781.0	8.6	70
163.	Cedar	781.0	8.6	70
164.	Cedar	781.0	8.6	70
165.	Cedar	781.0	8.6	70
69.	Kokomo Res. #2	484.0	7.0	66
	Nyona (S. Basin)	104.0	12.9	54

Group IV Subgroup D

109.	Yellow Creek	151.0	31.1	67
117.	Cotton	31.0	30.0	66
136.	Nauvoo	38.0	25.0	50
333.	Big Otter	69.0	25.8	52
451.	Loon	222.0	25.8	46

105.	Wabee	187.0	25.4	60
449.	Goose	84.0	25.9	61
455.	Troy-Cedar	93.0	27.3	60
342.	Little Otter	34.0	21.8	58
54.	Beaver Dam	146.0	22.5	55

Group V

6.	Yellowwood	133.0	14.2	11
137.	North Twin	135.0	15.7	13
82.	Kuhn	137.0	9.4	15
273.	Bass (St. Joseph Co.)	88.0	10.0	17
174.	Fishtrap	102.0	10.0	18
155.	Wall	141.0	11.6	13
407.	Elk Creek	47.0	12.5	13
114.	Brokesha	36.0	10.0	11
419.	Lime	30.0	11.0	10
418.	Lime	30.0	11.0	10
63.	Crystal	76.0	12.2	10
377.	Merom Gravel Pit	55.0	6.0	5
176.	Lower fish	134.0	6.5	8
115.	Cedar	120.0	8.5	9
30.	Heaton	87.0	7.4	10
154.	Stone	116.0	14.7	2
102.	Syracuse	414.0	12.9	4
11.	Deam	195.0	12.5	5

<u>Low Index Number Lakes</u>

	Bear Creek	7.0	10.0	7
	Crooked Creek	13.0	10.0	10
	Ogle	20.0	12.5	8
	Strahl	6.0	9.0	10
	Bowen	7.0	6.0	13
	Franke	9.0	7.8	35
	Oak	3.5	8.0	8
	Schlam	19.0	8.9	10
	Huntingburg City Lake	102.0	12.0	18
	Daniels	8.0	25.0	18
	Cline	20.0	17.5	9
	Meteer	18.0	8.3	17
	Weir	6.0	30.0	10
	Cherry	4.0	12.0	15
	Bryants Creek	9.0	10.0	15
	Hall	10.0	18.0	16
	Celina	164.0	15.0-20.0	10
	West	15.0	10.0	7
	Morgan	12.0	15.0	28
	Moss	9.0	9.0	24
	Failing	23.0	8.0	20
	Grass	20.0	10.0	24
	Loon	138.0	4.6	53
	Seven Sisters	22.0	14.0	27

	Walters	53.0	10.4	26
	Dollar	10.0	15.0	29

<u>High Index Number Lakes</u>

	Brodie Bed	19.0	4.0	64
	Halfmoon Bed	38.0	5.0	55
	Long Pond	38.0	4.0	58
	Mariah Pond	50.0	5.0	62
	Oaktown Bed	15.0	3.0	48
	Sandborn Old Bed	30.0	6.0	54
	Cypress	200.0	5.0	49
	Barrel	7.0	35.0	46
	Price	12.0	20.0	50
	Green (Rawles)	62.0	5.0	51
	Hayward	6.0	15.0	43
	Mongo Reservoir	24.0	15.0	54
	Nasby Mill Pond	35.0	10.0	41
	Spectacle Pond	6.0	7.5	52
	Star Mill Pond	38.0	10.0	43
	Horseshoe	35.0	3.0	60
	Lily	16.0	8.0	55
	Duely	21.0	8.6	42
	Hindman	13.0	10.8	52
	Indian (Village)	12.0	13.3	59
	Moss	9.0	8.9	51
	Rider	5.0	6.0	55
	Billington	11.0	10.0	35
	Canada	10.0	10.0	39
	Deep	7.0	15.0	22
	Hovey	242.0	4.0	60
	Mollenkramer	93.0	5.0	59
	Beaver Dam	11.0	15.0	27
	Deep	12.0	10.0	51
	Handy	16.0	18.1	35
	Shallow	65.0	5.0	51
	Stayner	5.0	7.0	51
	Warner	17.0	15.0	30
	Greenfield Bayou	61.0	5.0	52

Group VI Subgroup A

72.	Goose	27.0	20.0	15
296.	Gooseneck	25.0	20.0	15
394.	Pleasant (Steuben Co.)	53.0	22.5	20
416.	Kickapoo			
192.	Myers	96.0	20.8	21
153.	Still	30.0	20.7	19
121.	Eve	31.0	21.6	18
101.	Stanton	32.0	15.0	20
113.	Blackman	67.0	18.1	20
77.	Hoffman	180.0	17.6	23
131.	Messick	68.0	21.3	34
271.	Smalley	69.0	22.0	34

268.	Sacarider	33.0	22.4	35
236.	Latta	42.0	21.4	36
443.	Lukens	46.0	22.0	30
331.	Upper Long	86	22.1	32
442.	Blue	239.0	21.0	30
316.	Stienbarger	73.0	21.8	39
260.	Diamond	105.0	24.6	21
269.	Sand (Chain O'Lakes)	47.0	27.0	23
110.	Adams	308.0	25.0	28
146.	Pretty	184.0	25.7	25
453.	Round (Tri-Lake)	125.0	25.0	30
264.	Little Long	71.0	24.6	32
132.	Messick	68.0	21.3	26
267.	Round	99.0	21.6	24
388.	Flint	86.0	20.0	25
158.	Westler	88.0	20.1	25
157.	Westler	88.0	20.1	25
194.	Pretty	97.0	22.1	28
329.	Fox	142.0	22.2	27
148.	Royer	69.0	23.6	26
149.	Royer	69.0	23.6	26
94.	Sechrist	105.0	23.7	24
	Hill	66.0	19.4	31
	Oswego	41.0	20.0	33
	Barr	5.0	12.0	35
	Big Barbee	304.0	18.6	38
	Spear	18.0	25.0	36
	Nauvoo	38.0	25.0	50
	Pleasant	20.0	27.0/22.5	29
	Indian	149.0	15.0	20
	Saddle	41.0	15.0	36
	Tipsaw	131.0	15.0	19
	Clear	17.0	15.0	22
	Buck	20.0	15.0	30
	Gravel Pit	28.0	15.0	12
	Johnson	17.0	15.0	30
	Lake Anne	17.0	16.5	38
	Middle Fork Res.	277.0	15.0	18
	Little Crooked	15.0	20.0	32

Group VI Subgroup B

244.	Big	228.0	24.7	38
80.	James	282.0	26.9	39
79.	James	282.0	26.9	39

Group VI Subgroup C

301.	Hamilton	802.0	20.7	31

Group VII Subgroup A

106.	Webster	774.0	7.0	37
31.	Hunter	99.0	11.3	20

172.	Hog	59.0	11.7	21
184.	Holem	40.0	9.8	23
360.	Round B (Steuben)	30.0	11.3	23
371.	Walters	53.0	10.4	26
347.	Long B (Steuben)	154.0	11.9	24
84.	Little Chapman	177.0	11.2	25
230.	Engle	48.0	14.0	26
290.	Bell	38.0	13.4	24
283.	Hartz	28.0	13.2	23
365.	Silver	238.0	10.7	28
125.	Hackenberg	42.0	12.1	29
111.	Appleman	52.0	11.3	30
180.	Upper Fish	139.0	7.5	22
85.	Little Pike	25.0	5.6	31
370.	Tamarack	47.0	5.0	30
18.	Flat	26.0	8.1	35
207.	Clear	106.0	7.2	30
288.	Bass	61.0	7.4	31
277.	Riddles	77.0	8.3	30
389.	Long (Porter)	65.0	8.0	33
179.	Swede	33.0	8.0	32
40.	Lake 16	27.0	8.1	32
310.	Crooked (Middle Basin)	828.0	12.8	23
177.	Pine	282.0	13.0	22
208.	Hudson	432.0	11.7	23
414.	Quick Creek (Hardy)	705.0	12.5	19
58.	Big Chapman (W. Basin)	581.0	10.5	18
57.	Big Chapman (N. Basin)	581.0	10.5	18
	Indian Rock	100.0	10.0	37
	Grouse Ridge	20.0	10.0	25
	Sulphur	1.0	5.0	26
	Holland 1	17.0	10.0	27
	Holland 2	20.0	10.0	25
	Fish (Elkhart Co.)	34.0	10.0	35
	Anderson	14.0	5.0	31
	Zink	19.0	12.0	28
	Starve Hollow	145.0	6.8	58
	Brush Creek Reservoir	167.0	10.0	55
	Heron	22.0	12.0	22
	Sawmill	36.0	10.3	33
	Little Turkey	135.0	11.5	36
	Eddy	16.0	25.0	42
	Kreighbaum	20.0	20.0	32
	Bartley	34.0	12.6	35
	Knapp	88.0	25.0	43
	Port Mitchell	15.0	12.0	30
	Shockopee	21.0	13.3	30
	Springs Valley	141.0	8.0	20
	Hahn	8.0	6.0	46
	Liberty Park	11.0	7.0	26
	Oser	12.0	9.0	34
	Versailles	230.0	5.0	30
	Lincoln	58.0	12.0	29
	Quarry	43.0	15.0	30

	Gravel	12.0	10.0	19
	Green	24.0	10.0	15
	Meserve	16.0	14.0	22
	Mirror	9.0	13.3	25/12
	Lake Sullivan	507.0	10.0	39
	Green Valley	50.0	--	36
	Hartman	21.0	12.0	37
	Scott	18.0	5.0	23
	Waveland	360.0	10.0	20
	Prides Creek	90.0	10.0	33
Group VII Subgroup B				
38.	Fletcher	45.0	19.6	46
452.	Old	32.0	19.4	48
120.	Emma	42.0	16.7	44
318.	Tamarack	50.0	17.6	42
59.	Caldwell	45.0	17.8	46
243.	Bear	32.0	12.2	54
231.	Gordy	31.0	21.9	43
64.	Dewart (SE. Basin)	551.0	16.3	36
65.	Dewart (SW. Basin)	551.0	16.3	36
66.	Dewart (NW. Basin)	551.0	16.3	36
303.	Big Turkey	450.0	16.2	44
187.	Lake of the Woods	416.0	16.4	42
195.	Boggs Creek	600.0	12.5	45
62.	Center	120.0	17.2	31
145.	Pigeon	61.0	19.0	27
328.	Pleasant (St. Joseph)	29.0	18.0	29
262.	Gilbert	28.0	17.5	28
237.	Millers	28.0	14.6	35
265.	Long (Chain O'Lakes)	40.0	15.8	33
249.	Long (At Laketon)	48.0	16.0	30
287.	Barton	94.0	14.3	32
216.	Dixon	33.0	14.5	30
215.	Cook	93.0	17.7	40
254.	Bixler	120.0	17.4	38
245.	Cree	58.0	15.7	39
373.	West Otter	118.0	16.6	35
	Upper Summit	6.0	15.0	42
	Carr	79.0	17.0	50
	Little Barbee	74.0	13.0	56
	McClures	32.0	12.8	51
	Ridinger	136.0	21.0	58
	Rainbow	16.0	15.6	31
	Bowen	30.0	15.0	41
	Crane	28.0	12.9	45
	Dock	16.0	16.6	38
	Harper	11.0	14.5	60
	High	123.0	10.1	53
	Rivir	24.0	15.8	38
	Eliza	45.0	15.0	42
	Bischoff	200.0	15.0	63
	Black	18.0	15.0	36

	Crockett	5.0	15.0	49
	Henry	20.0	15.0	38
	Mud B	16.0	18.0	59
	Perch	12.0	18.0	30
	Whitewater	199.0	15.0	29
	Fowler Park	50.0	15.0	50
	Rockville	100.0	15.0	47

Group VII Subgroup C

78.	Irish	182.0	12.8	45
270.	Skinner	125.0	14.0	45
320.	Waldron	216.0	14.4	43
256.	Crane	28.0	12.9	45
238.	Muncie	47.0	12.3	46
185.	Koontz	346.0	9.2	42
395.	Lake Pleasant	424.0	8.2	40
20.	Cedar	28.0	8.2	40
412.	Spectacle	62.0	8.7	40
307.	Cheeseboro	27.0	10.0	40
88.	Muskelonge	32.0	9.4	40
221.	Griffey Res.	130.0	10.0	40
434.	Round (at Laketon)	48.0	11.2	43
152.	Star Mill Dam	38.0	10.0	43
345.	Lime-Kiln	25.0	10.0	42
60.	Boner	40.0	9.2	43
128.	Little Turkey	135.0	11.5	36
396.	Shakamak	56.0	10.9	38
241.	Bartley	34.0	12.6	35
93.	Sawmill	36.0	10.3	33
29.	Fish	34.0	10.0	35
272.	Sparta	31.0	5.5	40
2.	Rainbow (Adams Co.)	45.0	6.0	41
	Cedar (Dekalb Co.)	28.0	8.2	40
	Boner	40.0	9.2	43
	Saddle (Adams Co.)	24.0	10.0	41
	Muskelonge	32.0	9.4	40
	Crane	58.0	3.0	50
	Griffy Res.	130.0	10.0	40
	Horseshoe	18.0	13.9	40
	Sparta	31.0	5.5	40
	Oriole	1.0	5.0	39
	Mink	35.0	10.0	50
	Spectacle	62.0	8.7	40
	Eagle	24.0	6.7	40
	Langenbaum	48.0	5.4	41
	Cheeseboro	24.0	10.0	40
	Lime-Kiln	24.0	10.0	42
	Mud C	20.0	6.0	48
	Scales	66.0	7.0	50
	Jonay Reservoir	11.0	6.0	32
	Shackamack	56.0	10.9	38

Harold L. BonHomme
1932-1995

Harrold BonHomme was retired biologist

Harrold Lee BonHomme, 62, Goudland, Fla., formerly of Indianapolis, a retired senior biologist for the Indiana Department of Environmental Management, died Saturday.

A 26-year employee of the environmental agency, he was largely responsible for developing a classification system for lakes' trophic natures. Mr. BonHomme also provided testimony in enforcement actions to improve water quality throughout the state. He retired in 1991.

He was a Marine Corps veteran and a graduate of Vincennes and Indiana universities.

Memorial contributions may be made to Indiana's Endangered Wildlife Fund, 402 W. Washington St., Room W273, Indianapolis, Ind. 46204-2267.

There will be no services or calling.

Survivor: brother Gary BonHomme.

Joshburger Funeral home, Marco Island, Fla., is handling arrangements.

Thespian

Fine club bar -- lined with clique and monied crowd --
"Set 'em all up," I said -- too jovial and loud.
Fingering all that remained of my last pay --
Hoping elite drinkers would pause and glance my way.
Falsely dressed and status caught -- trying to be a man I'm no

Ranchos de Taos -- gentle people circled on earthen floors --
We are smoking grass and sipping Coors.
Too long of tooth -- alien to rap of life and pot --
Trying to be a man I'm not.

War torn Rhodesia -- following the mercenary trade --
Trained up tough --- almost made the grade.
Black terrorists -- roped and questioned on their knees --
Get answers or waste each of these.
Failing -- Too soft to fire that fatal shot
-- I could not become a man I'm not.

My role is cast in dim mise en scene --
I cannot find the man I might have been.
He is lost with his soul where past centuries meet --
or has yet to die in Third World heat.
Performing -- searching in varied spot
-- I shall never find the man I'm not.

--Harold L. BonHomme